Title	Paleomagnetism on the western part of Southwest Japan:tectonics in the edge of the rotated block(Dissertation_全文)
Author(s)	Ishikawa, Naoto
Citation	Kyoto University (京都大学)
Issue Date	1992-03-23
URL	http://dx.doi.org/10.11501/2964419
Right	
Type	Thesis or Dissertation
Textversion	author

学位申請論文

石川尚人

Paleomagnetism on the western part of Southwest Japan: tectonics in the edge of the rotated block

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A doctoral dissertation
submitted to Department of Geology and Mineralogy,
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1991

Abstract

Paleomagnetic measurements were performed on Eocene to Miocene sediments on the northern Kyushu Island in order to clarify the manner of the clockwise (CW) rotation of Southwest Japan at 15 Ma. Paleomagnetic directions indicate that Northern Kyushu was rotated $28^\circ \pm 14^\circ$ between 30 and 14 Ma relative to northern Eurasia, while no significant rotation has taken place in Western Kyushu since 30 Ma.

The western extent of Southwest Japan which experienced the Middle Miocene CW rotation is truncated at the west of Northern Kyushu. The amount of rotation for the western part of Southwest Japan ($\sim 28^\circ$) is smaller than that for the main part ($\sim 50^\circ$), indicating deformation on the edge of the rotated block.

The transpressional deformation event in the Tsushima Strait area was coeval with the CW rotation of Southwest Japan. The deformation event is attributed to the CW rotation of Southwest Japan about a pivot on the western part, followed by northwestward translation of Western Kyushu.

The convergent tectonic around the western part of Southwest Japan suggests that the area had been situated southward relative to the present position before the CW rotation. The southward translation may be inferred for Southwest Japan prior to the CW rotation, which is possibly linked to parallel opening of the Japan Sea before fan-shape spreading at 15 Ma.

1.Introduction

The Japanese Island arcs are continental slivers drifted from the Asian continent in the formation of the Japan Sea back-arc basin (e.g., Uyeda and Miyashiro, 1974). Paleomagnetism on the arcs has documented the mode of drifting of slivers (Otofuji and Matsuda, 1983, 1987; Hayashida and Ito, 1984; Hayashida, 1986; Otofuji et al., 1985a, 1985b, 1985c, 1991; Tosha and Hamano, 1988; Hayashida et al., 1991). Otofuji et al. (1985c) demonstrated the clockwise (CW) rotation of about 50° at about 15 Ma for the southwest part of the Japanese Island arcs (Southwest Japan).

In Southwest Japan, pre-Neogene geologic units are zonally arranged with ENE-WSW structural trend (Ozawa et al., 1984). The zonal structure is traced continuously throughout the landmass (Fig. 1). On the basis of the zonal structure, the rigid block rotation model has been proposed for the CW rotation of Southwest Japan on the first approximation (Otofuji et al., 1985c; Otofuji and Matsuda, 1987).

Paleomagnetic data from San'in to Tokai districts in the main part of Southwest Japan (Fig. 1) have supported the rigid block rotation model because of no discrepancy among the data (Otofuji et al, 1985c; Hayashida, 1986). Paleomagnetic directions from the easternmost part of Southwest Japan showed smaller amount of CW rotation than that for the main part (Itoh, 1988; Itoh and Ito, 1989). The amount of differential rotation to the main part increased toward the Itoigawa-Shizuoka Tectonic Line (Fig. 1), which bounds the eastern end of Southwest Japan (Itoh and Ito, 1989). Itoh and Ito (1989) interpreted the differential rotation by ductile deformation of the easternmost part. Although the northern Kyushu Island has been assumed as the western extent of the rigid block based on the zonal structure of Southwest Japan (Otofuji and Matsuda, 1987), the assumption for the coherent tectonic block has never been assessed paleomagnetically in the Kyushu Island.

The CW rotation of Southwest Japan based on the rigid block rotation model has been linked to the opening of the Japan Sea at about 15 Ma (e.g., Otofuji et al., 1985c). The rotation pivot of the rigid block has been located in the Tsushima Strait area, near its western margin (34°N and 129°E; Otofuji and Matsuda, 1983). When Southwest Japan is rotated back to the Asian continent about the pivot, the Japan Sea is almost closed (Otofuji and Matsuda, 1983). The age of the CW rotation has been thus taken as the formation age of the Japan Sea. On the other hand, geological and geophysical evidence for older

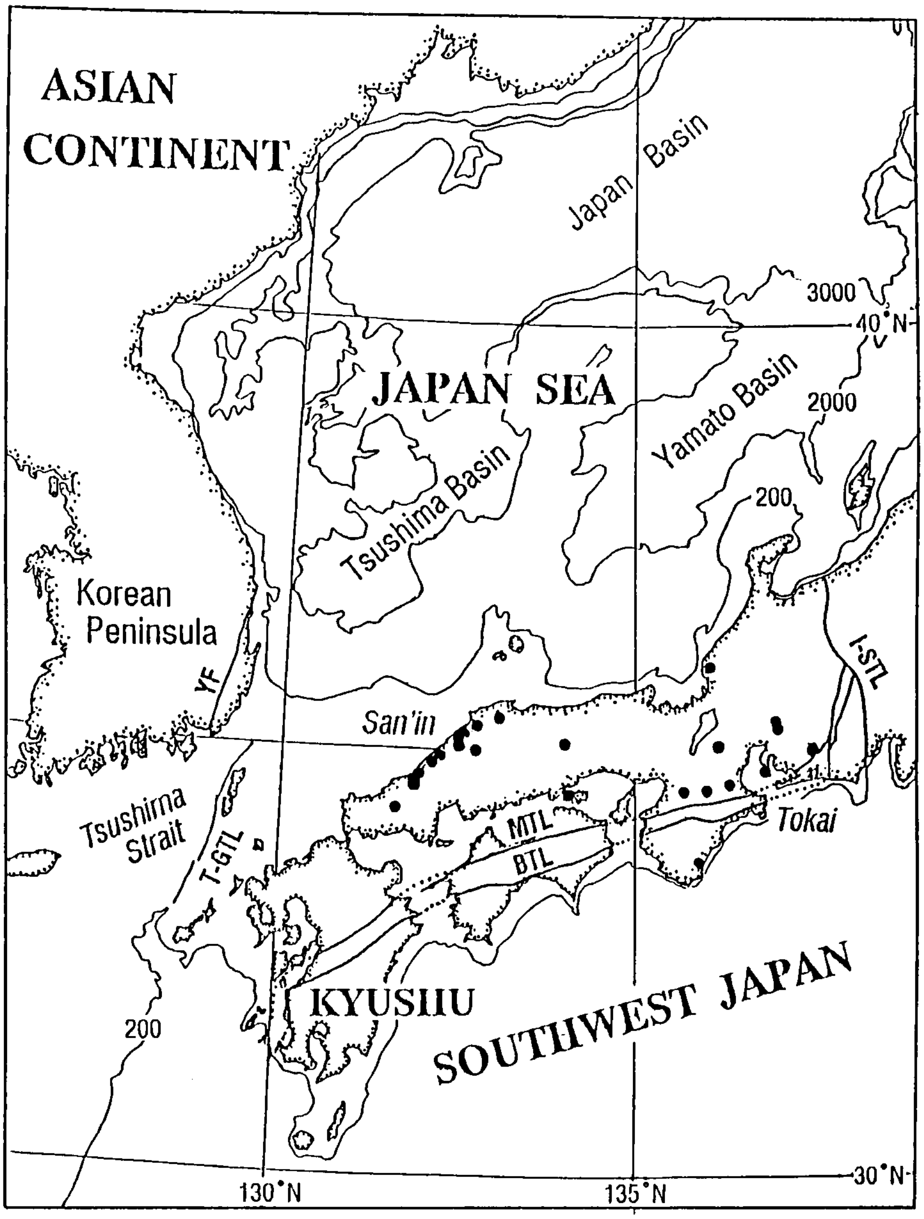

Fig. 1. Map showing the present configuration of the island- arc—back-arc basin system around the the Japan Sea. Median Tectonic Line (MTL) and Butsuzo Tectonic Line (BTL) represent the general trend of the zonal structure of the pre- Neogene geologic units in Southwest Japan. Solid circles denote localities of paleomagnetic data before about 15 Ma which have documented a clockwise rotation of the coherent Southwest Japan block (Otofuji et al., 1985c; Hayashida, 1986; Nakajima and Hirooka, 1986; Otofuji and Matsuda, 1987; Fukuma and Torii, 1990; Hayashida et al., 1991; Otofuji et al., 1991). I-STL:Itoigawa-Shizuoka Tectonic Line, T-GTL:Tsushima- Goto tectonic line, YF:Yangsan Fault.

initiation of the Japan Sea has been accumulated from on-land and the Japan Sea (Tamaki, 1986; Isezaki, 1986; Ingle et al., 1990; Kaneoka et al., 1990, 1991: Tamaki et al., 1990).

The purpose of this article is to assess the rigid block rotation model for the CW rotation on the western part of Southwest Japan. Paleomagnetic measurements were carried out on samples from Tertiary sediments distributed in the northern Kyushu Island (Fig. 2). Paleomagnetic directions from the region is crucial to reveal the manner of the CW rotation of Southwest Japan and associated tectonics around its western margin. Ishikawa et al. (1989) and Ishikawa and Tagami (1991) performed paleomagnetic and geochronologic investigations on the Tsushima and Goto Islands in the Tsushima Strait area (Fig. 1). These works revealed the early to middle Miocene compressive deformation event in the Tsushima Strait area, followed by the counter-clockwise (CCW) rotations of the two archipelagoes at around 15 Ma. In conjunction with these tectonic movements, the manner of the CW rotation of Southwest Japan will be discussed in this study.

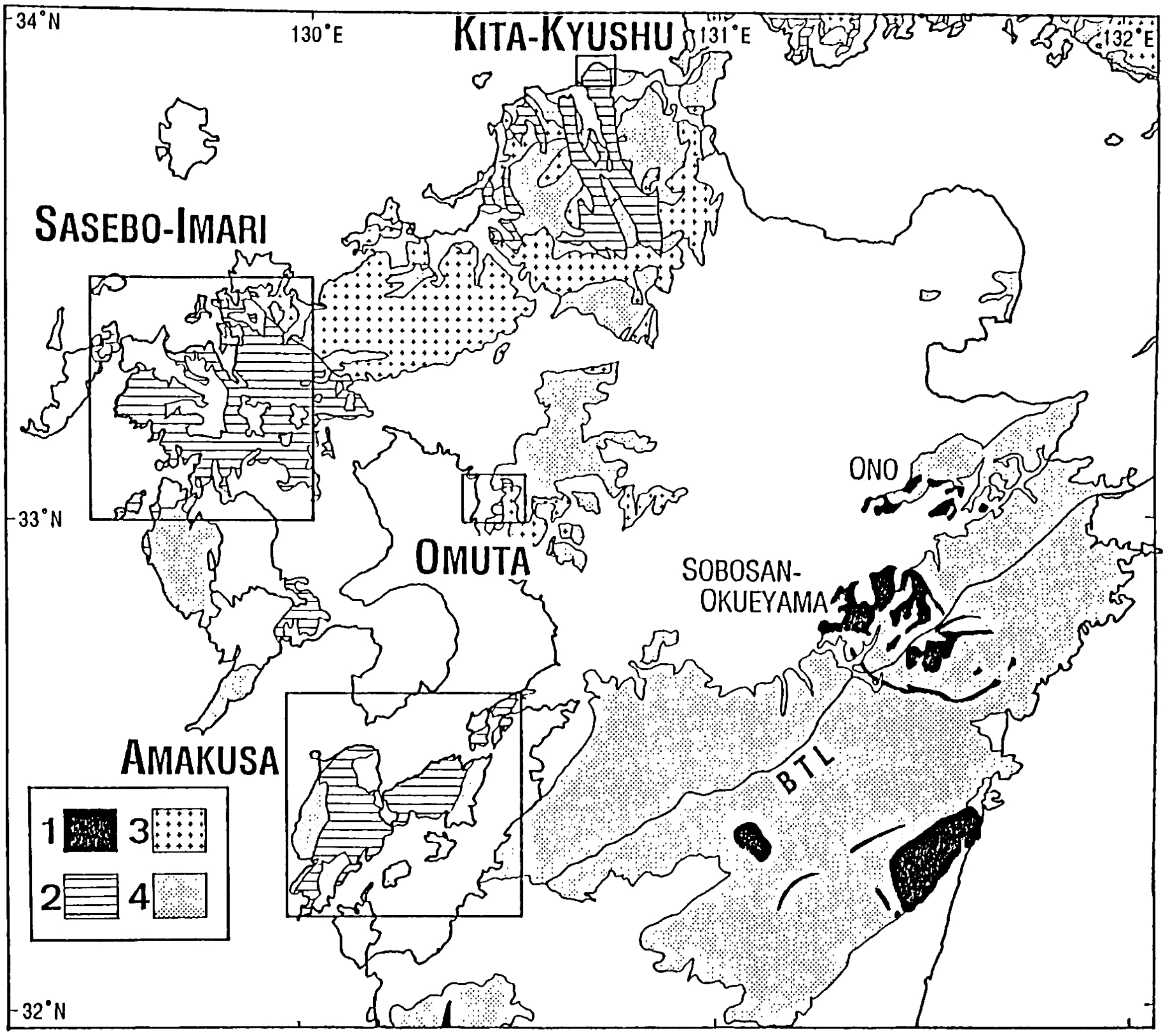

Fig. 2. The simplified geological map of the northern Kyushu Island. 1:Middle Miocene igneous rocks, 2:Paleogene to Miocene sedimentary sequences, 3:late Cretaceous granitic rocks, 4: other pre-Neogene geologic units. Paleomagnetic samples were collected from the areas enclosed by rectangles.

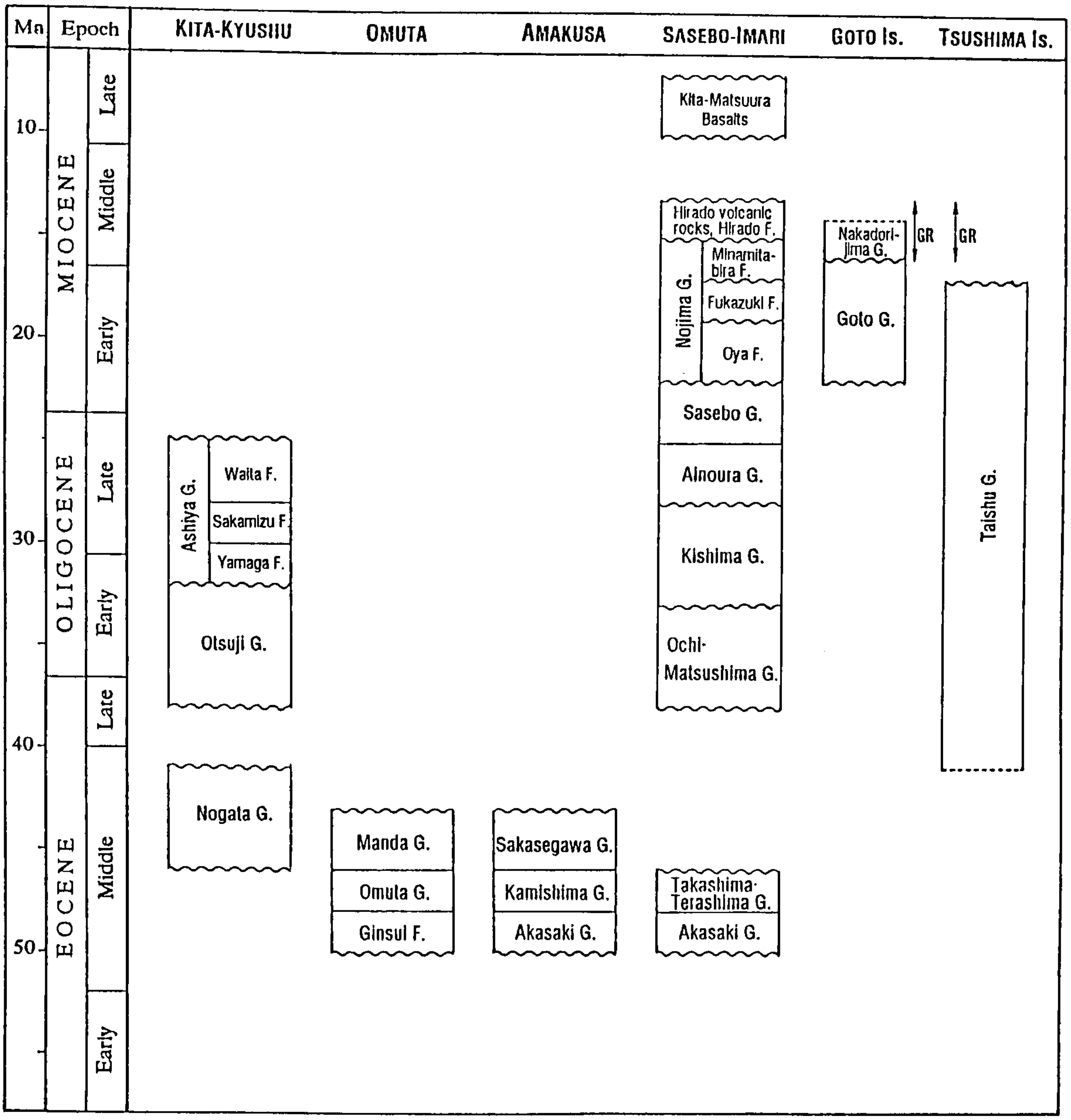

Fig. 3. Stratigraphic correlation among the Paleogene to Miocene rocks in sampling areas and the Goto and Tsushima Islands (after Kano et al.(1991), Sakai and Nishi (1990), Tashiro et al. (1980), and Miki (1981)).

2.Geological setting of the studied areas

The coal-bearing Paleogene sedimentary sequences are widely distributed in the northern Kyushu Island. Neogene sequences are disposed in the northwestern part, overlying the Paleogene sequences unconformably (Fig. 2). Paleomagnetic studies were performed on these Paleogene and Neogene sedimentary rocks at the four areas: the Sasebo-Imari, Kita-Kyushu, Amakusa, and Omuta areas (Figs. 2 and 3)

Sasebo-Imari area

Paleogene to middle Miocene sediments are distributed at the Sasebo-Imari area (Fig. 4). The sediments overly the late Cretaceous granitic rocks, the Nagasaki metamorphic rocks and mylonitic granites. The sediments are overlain by Late Miocene Kita-Matsuura basalts and the other late Miocene or younger volcanic rocks. Tuff and mudstone samples were collected at 16 sites: five sites of the Kishima Group, three of the Ainoura Group, two of the Sasebo Group and six of the Oya Formation of the Nojima Group (Figs. 3 and 4).

The geologic age of each sedimentary unit has been estimated based on paleontological and radiometric age data (e.g., Kano et al., 1991). The Kishima Group yields abundant marine fossils of the Ashiya fauna, and has been correlated to the Ashiya Group. The Ainoura Group yields abundant plant fossils, the Ainoura type flora, and marine fossils of the Ashiya fauna. The Sasebo Group yields plant fossils of the Aniai-type flora. Sakai et al. (1990) found planktonic foraminifera assigned to P.21 to N.4 in Blow's zone (Blow, 1969) from the upper part of the group. The Oya and Fukazuki Formations of the Nojima Group yields plant fossils of the Daijima-type flora. Two zircon fission-track ages of 18.5±2.3Ma and 18.9±2.9Ma were determined on two samples from tuff beds at the basal part of the Fukazuki Formation (Sakai et al., 1990). The age of collected samples ranged from Oligocene to Early Miocene.

Kita-Kyushu area

The Paleogene sediments in the Kita-Kyushu area are divided into three groups: the Nogata, Otsuji, and Ashiya Groups in ascending order (Fig. 3). The sediments overly the Cretaceous granitic rocks and the basement rocks of the Permian Sangun metamorphic

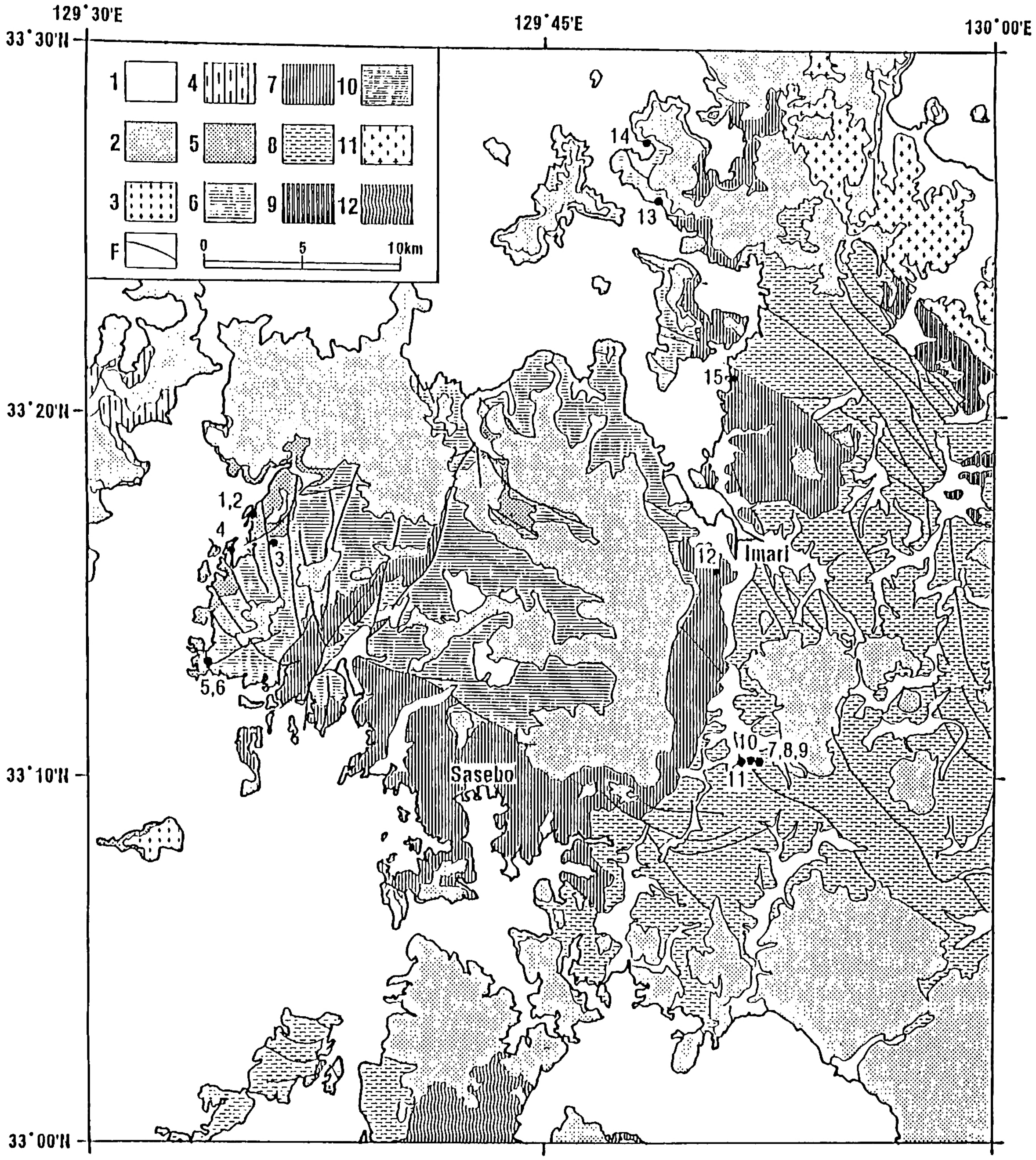

Fig. 4. Locations of sampling sites (solid circles with numerals) in the Sasebo-Imari area. Geological map was simplified from Geological Survey of Japan (1959 and 1989). 1:Alluvium, 2:Late Miocene or younger volcanic rocks, 3:middle Miocene granitic rocks, 4:Hirado Formation, 5:Nojima Group, 6:Sasebo Group, 7:Ainoura Group, 8:Kishima Group, 9:Ochi and Matsushima Group, 10:Takashima, Terashima and Akasaki Groups, 11:late Cretaceous granitic rocks, 12: Nagasaki metamorphic rocks, F:faults.

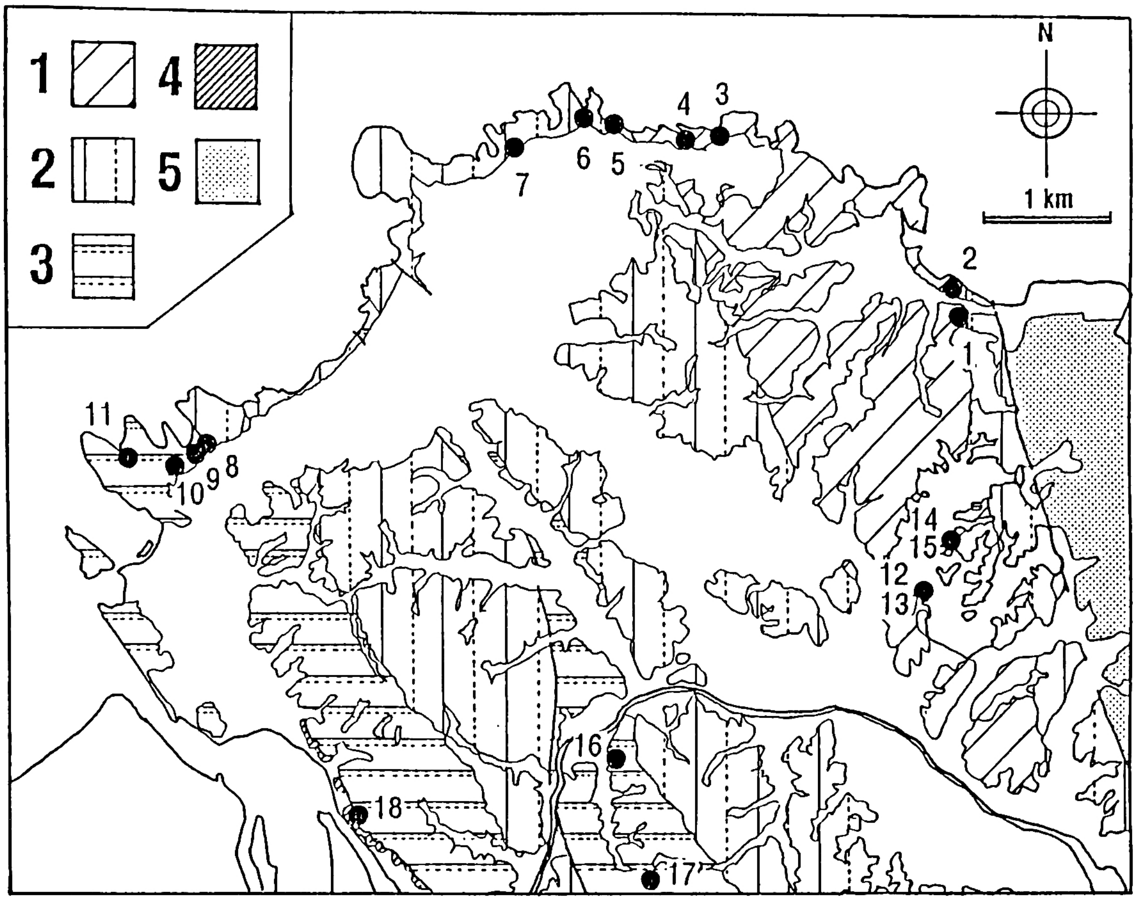

Fig. 5. Locations of sampling sites (solid circles with numerals) in the Kita-Kyushu area. Geological map was simplified Tsuchi et al. (1987). 1:Waita Formation, 2:Sakamizu Formation, 3:Yamaga Formation, 4:Otsuji Group, 5:Mesozoic rocks.

rocks, the Paleozoic sedimentary rocks, and the late Cretaceous Kanmon Group (Fig. 2). Paleomagnetic samples were collected at 18 sites of mudstone, fine sandstone and tuff from the Ashiya Group (Fig. 5).

The Ashiya Group is divided into three formations: the Yamaga, Sakamizu, and Waita Formations in ascending order (Fig. 3), and each formation is lithologically subdivided into two or three members. Tsuchi et al. (1987) obtained planktonic foraminifera assemblages assigned to P.21 in Blow's zone (Blow, 1969) from five horizons covering the whole group. Saito and Okada (1984) correlated calcareous nannoplankton assemblages from the upper part of the Yamaga Formation to CP 18. These micropaleontological data indicate that the whole Ashiya Group is probably assigned to the Oligocene in age (Tsuchi et al., 1987).

Amakusa area

Paleogene sediments at the Uto Peninsula and the Amakusa Islands in the Amakusa area overly the late Cretaceous Himeura Group unconformably (Fig. 6). The sediments cover the Nagasaki metamorphic rocks on the western coast of the Shimoshima Island (Fig. 6). The whole sequence of the Paleogene sediments is disposed at the Kamishima Island, and divided into three groups (Miki, 1981): the Akasaki, Kamishima, and Sakasegawa Groups in ascending order (Fig. 3). Planktonic foraminifera and radiolaria, of which ages were assigned to Middle Eocene, were found on the Shimoshima Island from the strata corresponded to the Kamishima and Sakasegawa Groups (Yasuda, 1984). Tashiro et al. (1980) obtained calcareous nannofossiles corresponding to *Discoaster sublodoensis* zone (48.0-49.5Ma) of Bukry (1973) from the beds corresponded to the Akasaki Group at the southernmost part of the Shimoshima Island.

Paleomagnetic measurements were performed on samples from the Akasaki Group. The Akasaki Group is mainly composed of purple-red mudstone and sandstone. Miki and Matsueda (1985) revealed that the pigmenting agent responsible for the characteristic color was hematite which filled interstices among the grains. They suggested that the hematite was supplied from schists and igneous rocks as detrital fine minerals and from ground water as hydroxide, which aged to hematite through diagenetic dehydration. Mudstone and sandstone samples with purple-red color were collected at eight sites in the

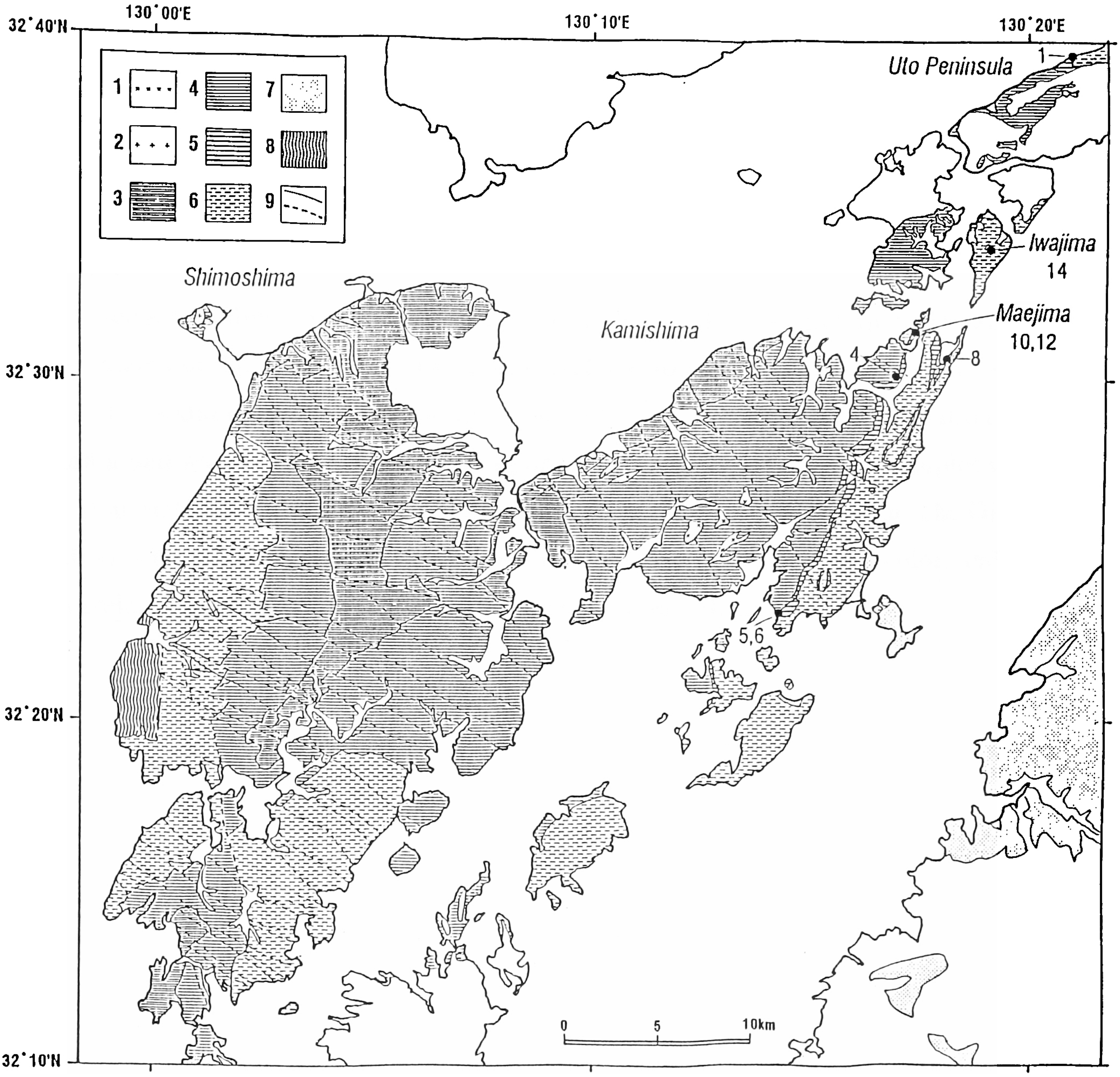

Fig. 6. Locations of sampling sites (solid circles with numerals) in the Amakusa area. Geological map was simplified from Miki (1981). 1:post-Paleogene volcanic dike rocks, 2:Miocene granodiorite, 3:Sakasegawa Group, 4:Kamishima Group, 5:Akasaki Group, 6:Himeura Group, 7:other pre-Neogene rocks, 8:Nagasaki metamorphic rocks, 9:faults.

Uto Peninsula and the Iwajima, Maejima and Kamishima islands (Fig. 6). The Paleogene sequences on the Kamishima Island have NNE- SSW trending fold axes, and bedding of the strata is generally 10° to 30° (Inoue, 1962; Miki, 1975). The strata in the Uto Peninsula generally dip 10°-20° to the west (Inoue, 1962; Miki, 1975).

Omuta area

Paleogene sediments in the Omuta area overly the Cretaceous granitic rocks and the Chikugo metamorphic rocks, which has been correlated to the Sangun metamorphic rocks (Fig. 7). The sediments are divided to three units (Miki, 1981); the Ginsui Formation and the Omuta and Manda Groups in ascending order (Fig. 3). Paleomagnetic samples were collected at eight sites of mudstone and sandstone from the Ginsui Formation. The Ginsui Formation is mainly composed of mudstone and sandstone with purple-red color, and has been correlated to the Akasaki Group in the Amakusa area (Miki, 1981).

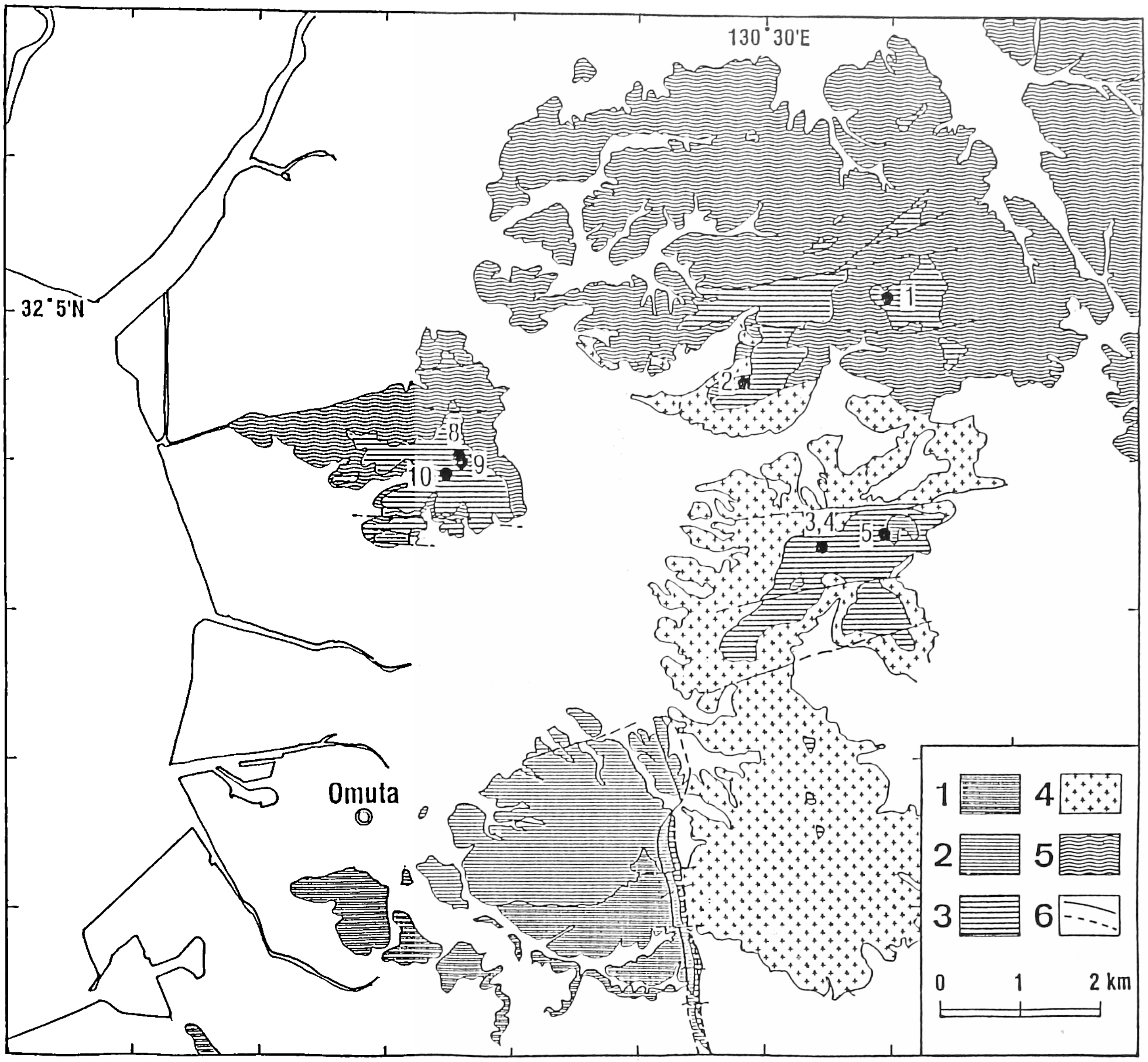

Fig. 7. Locations of sampling sites (solid circles with numerals) in the Omuta area. Geological map was simplified from Fukuoka Prefecture (1987). 1:Manda Group, 2:Omuta Group, 3:Ginsui Formation, 4:Cretaceous granitic rocks, 5:Chikugo metamorphic rocks.

3. Paleomagnetic analysis

3-1. Field and Laboratory procedures

Sedimentary rock samples were collected mainly using a gasoline-powered core drill and partially by hand sampling. Each site consists of six to fourteen core or block samples oriented by a magnetic compass. One or two cylindrical specimens of 24 mm in diameter and 22 mm in height were prepared from each sample. Cubic specimens of about 20 mm were prepared from broken hand samples during coring at the laboratory. Natural remanent magnetization (NRM) was measured by a cryogenic magnetometer (ScT C-112) at Department of Geology and Mineralogy, Kyoto University. The noise level of the magnetometer was 0.02 nAm^2.

Progressive thermal and alternating-field (AF) demagnetizations were performed on two or three pilot specimens from each site. Thermal demagnetization was made in a air using a noninductively wound electric furnace settled in a four-layered μ-metal magnetic shield. The stray field was reduced to less than 5 nT. AF demagnetization was made using a three-axis tumbler system contained in a three-layered μ-metal shield. Maximum peak field produced by the AF demagnetizer was 100 mT.

Pilot demagnetization result was plotted on both orthogonal vector-demagnetization diagram (Zijderveld, 1967) and equal-area projection. Individual magnetic components for each pilot specimen were picked on the basis of a linear decay of vector-end points toward the origin of the diagram. The vector-end points were sometimes aligned along a curved line decaying toward the origin on the diagram, which implied considerable overlap of unblocking temperature or coercivity spectra of two (or more) components. In such case, the vector-end points defined an arc of a great circle on the equal-area projection, which is called remagnetization circle (e.g., Halls, 1976). The remagnetization circles of pilot specimens of individual site tended to converged into a common direction. The common direction was considered to be the direction of the component with higher unblocking temperature or coercivity.

When pilot demagnetization results yielded the stable components shown as straight line decaying toward the origin of the diagram or the remagnetization circles on the equal-area projection, all remaining specimens of the site were progressively demagnetized. The direction of the stable component was obtained using principal component analysis (Kirschvink, 1980), anchored to the origin of the diagram. Site-mean directions of the stable components and associated statistical parameters were calculated (Fisher, 1953). The common direction sheared by the remagnetization circles was calculated using the method of McFadden and McElhinny (1988), if available, combining the directions of the stable component. The site-mean direction calculated by the two methods was regarded as a characteristic direction of the site.

3-2 Demagnetization results and characteristic directions

Sasebo-Imari area

The specimens of all sites in the Sasebo-Imari area except Sites 9 and 11 had intensity of initial NRM between the order of 10^{-9} to 10^{-8} Am^2. The intensities of the specimens of Sites 9 and 11 were the order of 10^{-10} Am^2. The unstable components with normal polarity, probably viscous overprint of the recent geomagnetic field direction, were generally erased in the lower demagnetization range approximately below 240°C and/or 10 mT (Fig. 8). After removal of the unstable component, the specimens of seven sites among 16 sites yielded one or two magnetic components.

The specimens of Sites 5 and 10 yielded the stable components in the temperature range between 360°C and 600°C (Fig. 8-1). The stable components of the two sites were recognized as a straight line toward the origin. The specimens of Sites 6 and 12 provided approximate linear decay of the vector-end points toward the origin in the demagnetization range from 240°C to 360°C or 470°C, while those of Site 13 in the range between 10 mT and 20 mT for Site 13 (Fig. 8- 2). The erratic behaviors of the remanence occurred in higher demagnetization levels for the specimens of Sites 6, 12 and 13.

Two specimens among nine specimens of Site 11 yielded the stable components decaying toward the origin in the demagnetization range between 10 mT and 25 mT (Fig. 8-3a). The other two specimens provided remagnetization circles in the range from 5 mT to 15 mT (Fig. 8-3b), followed by unstable behaviors of the remanence because of the very weak intensities ($<1\times10^{-11}Am^2$). Intensities of NRMs of the rest five specimens were initially very weak. A characteristic site mean direction of Site 11 was calculated by combining the two remagnetization circles with the two directions of the stable components based on the method of McFadden and McElhinny (1988) as shown in Fig. 8-3c.

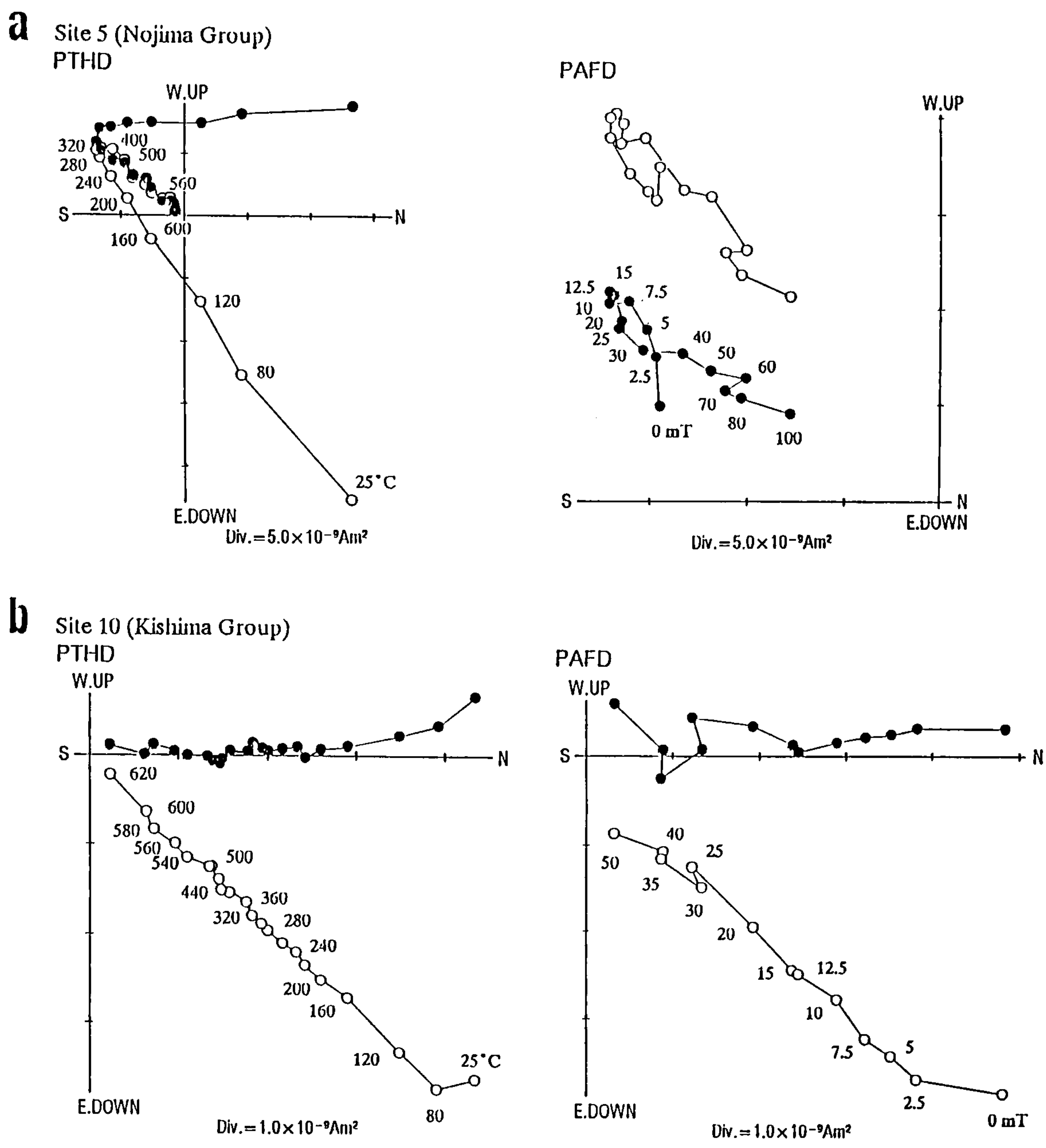

Fig. 8-1. Vector-demagnetization diagrams of progressive demagnetization for samples from the Sasebo-Imari area. Stable component was recognized as a straight line toward the origin on the diagram. Solid and open circles are projections on horizontal and N-S vertical planes, respectively. PTHD:progressive thermal demagnetization, PAFD:progressive alternating field demagnetization.

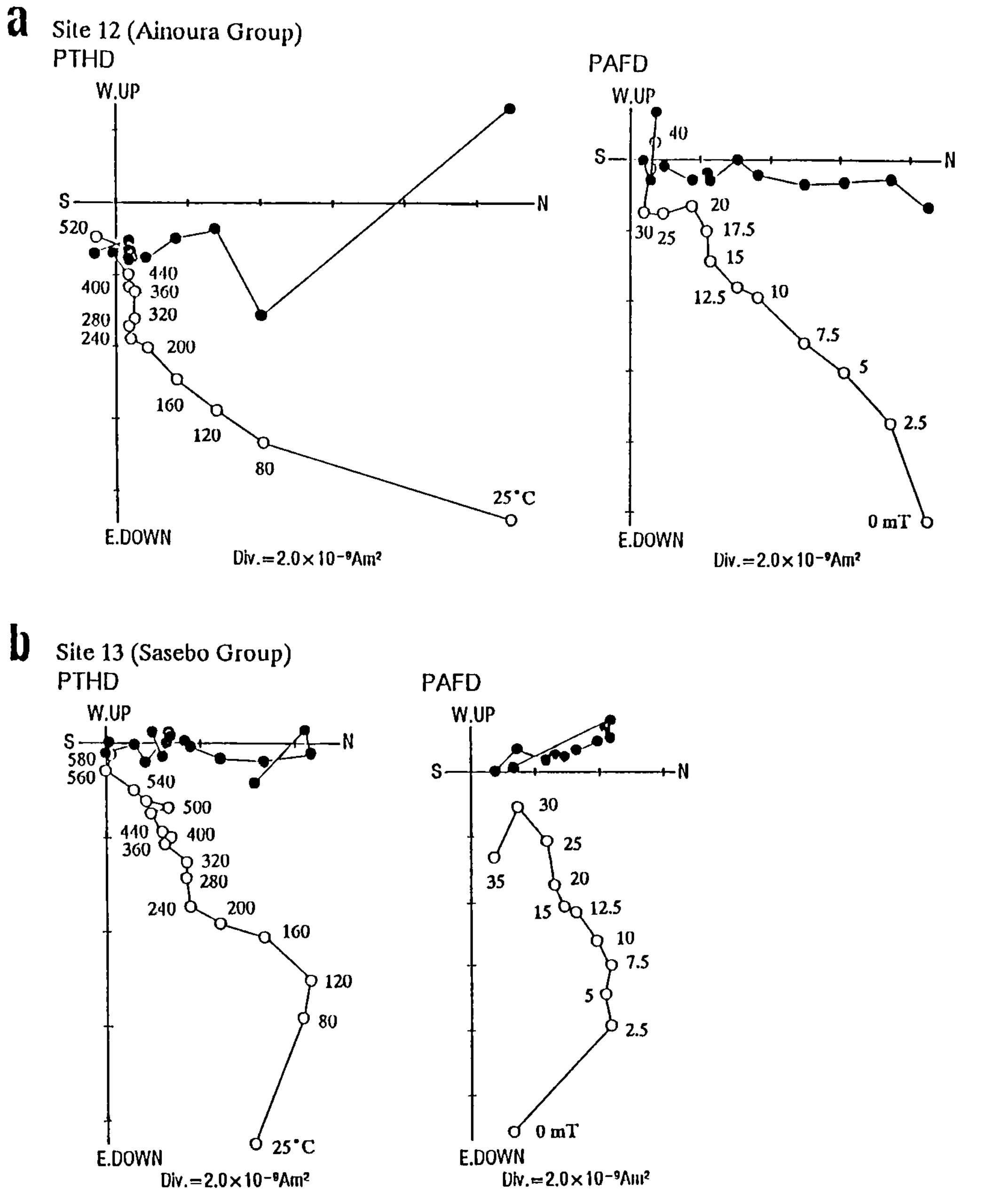

Fig. 8-2. Vector-demagnetization diagrams of progressive demagnetization for samples from the Sasebo-Imari area. Stable component shown as straight line decaying toward the origin on the diagram were isolated more effectively by the PTHD (a) or the PAFD (b). Symbols are the same as in Fig. 8- 1.

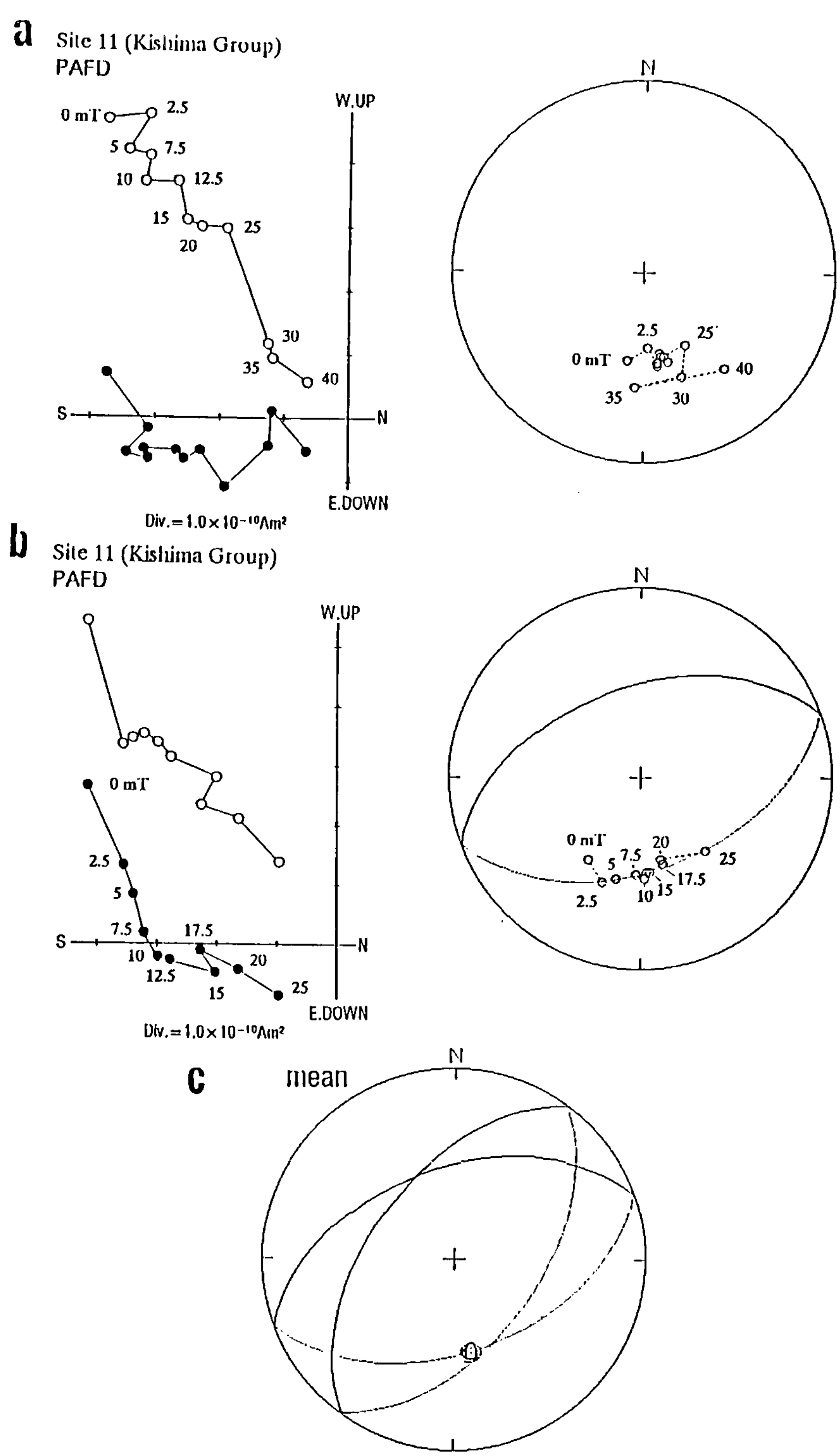

Fig. 8-3. Progressive demagnetization results and site-mean direction from Site 11 in the Sasebo-Imari area. a and b: magnetic behaviors during progressive AF demagnetization on vector-demagnetization diagram (left) and equal-area projection (right). Open circles on equal-area projection are on the upper hemisphere. a: this demagnetization result provided stable component. b: this demagnetization result provided remagnetization circle. The remagnetization circle was fitted by least-square great circle. c: a site- mean direction of Site 11 (open square with oval) was obtained by combining the remagnetization circles as shown in (b) into the direct directional data (open circles) as shown (a) after McFadden and McElhinny (1988). Oval around the site-mean direction indicates 95% confidence limit.

The demagnetization results from the three specimens of Site 8 showed the existence of two magnetic components in the temperature range between 320°C and 620°C (Fig. 8-4). One specimen among the three provided the linear decay of the vector-end points toward the origin between 540°C and 620°C (Fig. 8-4a). The higher-temperature component had north declination with positive inclination. The remagnetization circles of the rest two specimens in the temperature range between 320°C and 540°C implied the existence of the components similar to the high-temperature component (Fig. 8-4b). The site mean direction of the higher temperature components was calculated by combining two remagnetization circles with one directional datum as shown in Fig. 8-4c.

The characteristic directions were obtained from seven sites among 16 sites (Table 1); two sites from the Oya Formation of the Nojima Group, one from the Sasebo Group, one from the Ainoura Group, and three from the Kishima Group. The radius of 95% confidence circle of Site 8 was larger than 20°, while those of other sites were smaller. The direction of Site 8 was discarded from the further consideration. Four site mean direction among the rest six sites had north declination with positive inclination in in-situ coordinates, and the other two had south declination with negative inclination (Fig. 9). Although the in-situ directions with normal polarity were close to the present geomagnetic field direction, the demagnetization results showed that viscous overprints of the recent geomagnetic field were erased at the lower demagnetization levels. The untilted directions showed a better antipodal relationship in a north-to-south trend than the in-situ directions (Fig. 9; Table 1), although the fold test of McElhinny (1964) did not pass at the 95% confidence level (k2/k1=1.61;*i.e.*, the ratio of precision parameter before [k1] and after [k2] tilt correction). The antipodal relationship indicated that the untilted directions represented the directions of the ancient geomagnetic field at the time of the deposition. The overall mean of the untilted directions (D=-7.0°, I=52.9°, α_{95}=9.7, and k=48.8) was considered to be a mean paleomagnetic direction of the Kishima to the Nojima Groups, namely Oligocene to Early Miocene in the Sasebo-Imari area.

Kita-Kyushu area

Intensities of initial NRM of the specimens from the Ashiya Group ranged form 2×10^{-9} to 5×10^{-8} Am^2. The NRM of the specimens generally showed erratic changes in

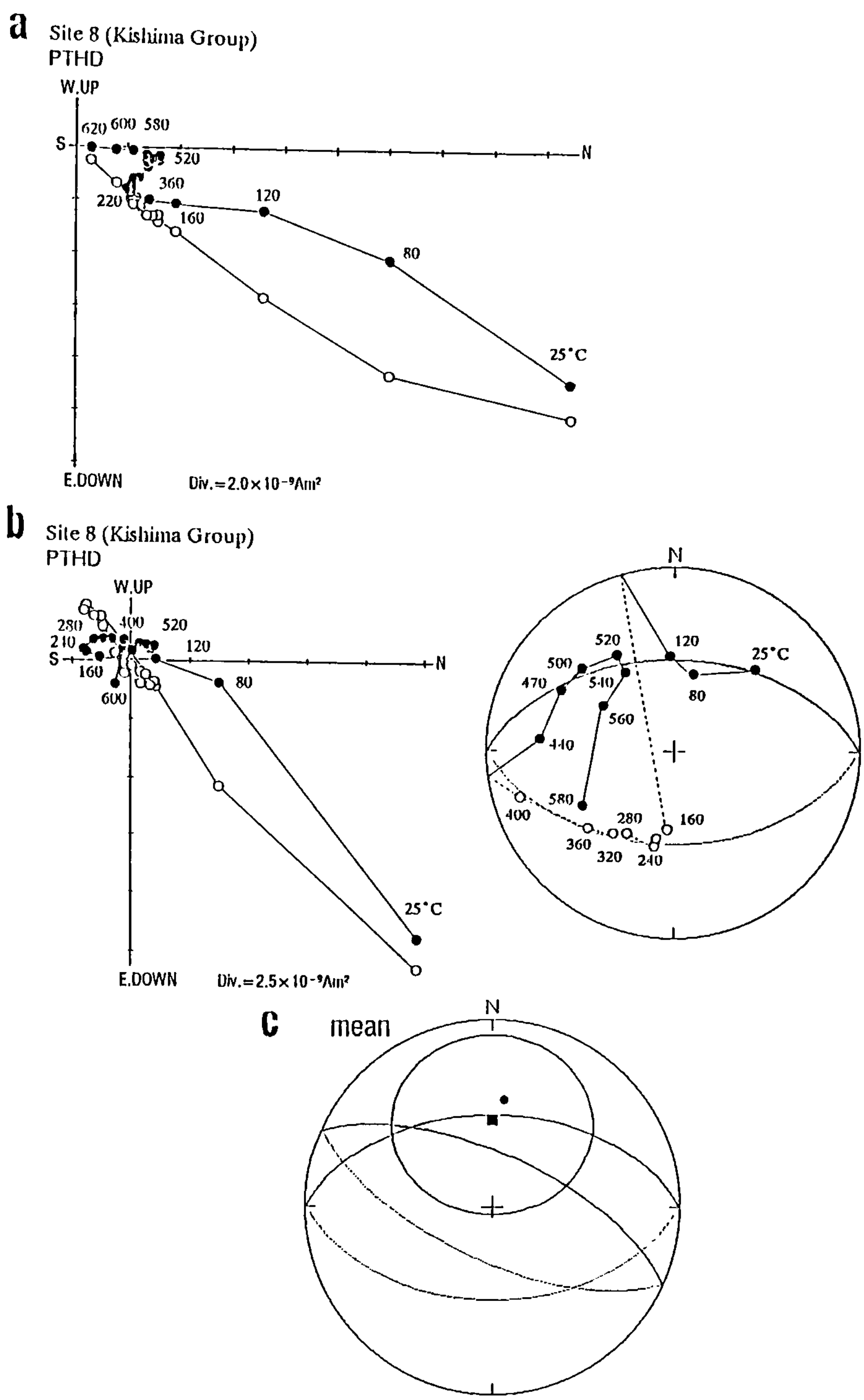

Fig. 8-4. Progressive demagnetization results and site-mean direction from Site 8 in the Sasebo-Imari area. a: vector-demagnetization diagrams of progressive thermal demagnetization. This demagnetization result provided stable component. b: vector-demagnetization diagrams (left) and equal-area projection (right) of progressive thermal demagnetization. Solid and open circles on equal-area projection are on the lower and upper hemispheres, respectively. This demagnetization result provided remagnetization circle. The remagnetization circle was fitted by least-square great circle. c: a site-mean direction of Site 8 (Solid square) was obtained by combining the remagnetization circles as shown in (b) into the direct directional data as shown (a) after McFadden and McElhinny (1988). Oval around the site-mean direction indicates 95% confidence limit.

Table 1. Paleomagnetic data from the Sasebo-Imari area.

Site (Lat, Lon)	N	levels	D	I	D*	I*	α_{95}	k	PLAT*	PLON*
Nojima Group										
5 (33°13.1', 129°34.0')	6	LA 360-620°C	-154.2°	-39.6°	-172.0°	-44.4°	6.0°	127.6	80.0°	-96.8°
6 (33°13.1', 129°34.0')	4	LA 320-560°C	2.5°	41.1°	-14.7°	39.6°	18.6°	25.4	73.2°	3.6°
Sasebo Group										
13 (33°26.1', 129°48.8')	4	LA 10-25mT	-6.2°	59.8°	-23.5°	54.9°	18.1°	26.8	70.6°	52.3°
Ainoura Group										
12 (33°16.7', 129°50.8')	6	LA 200-320°C	27.3°	61.5°	4.3°	62.0°	19.8°	12.4	79.5°	147.3°
Kishima Group										
8 (33°10.4', 129°52.2')	1	LA 500-620°C	-6.0°	51.0°	-4.2°	61.8°	42.3°	24.6		
	2	GC 280-520°C								
10 (33°10.5', 129°51.8')	6	LA 300-600°C	-4.5°	45.0°	0.6°	54.0°	7.5°	151.6	88.6°	149.8°
11 (33°10.4', 129°51.5')	2	LA 5-20mT	163.4°	-48.6°	163.2°	-58.6°	4.3°	617.3	75.2°	69.1°
	2	GC 0-12.5mT								
mean	6		4.4°	50.4°			12.4°	30.3		
mean*	6				-7.0°	52.9°	9.7°	48.8	84.1°	49.7°
									(α_{95}=11.1°, k=37.3)	

Note: Site: site number, (Lat, Lon): latitude (N) and longitude (E) of locality of the site. N: number of specimens (sites). levels: demagnetization levels in which least-square line-fitting including toward the origin of the vector-demagnetization diagram (LA) and least-square great circle fitting (GC) were applied after Kirschvink (1980) and McFadden and McElhinny (1988), respectively. D,I: declination and inclination in in-situ coordinates was observed. D*,I*: declination and inclination after tilt correction, respectively. α_{95}: radius of 95% confidence circle. k:precision parameter. PLAT,PLON: latitude (N) and longitude (E) of the north-seeking virtual geomagnetic pole (VGP) position calculated from the in-situ site-mean direction (north-seeking pole), respectively. PLAT*,PLON*: latitude (N) and longitude (E) of the north-seeking virtual geomagnetic pole (VGP) position calculated from the untilted site-mean direction, respectively.

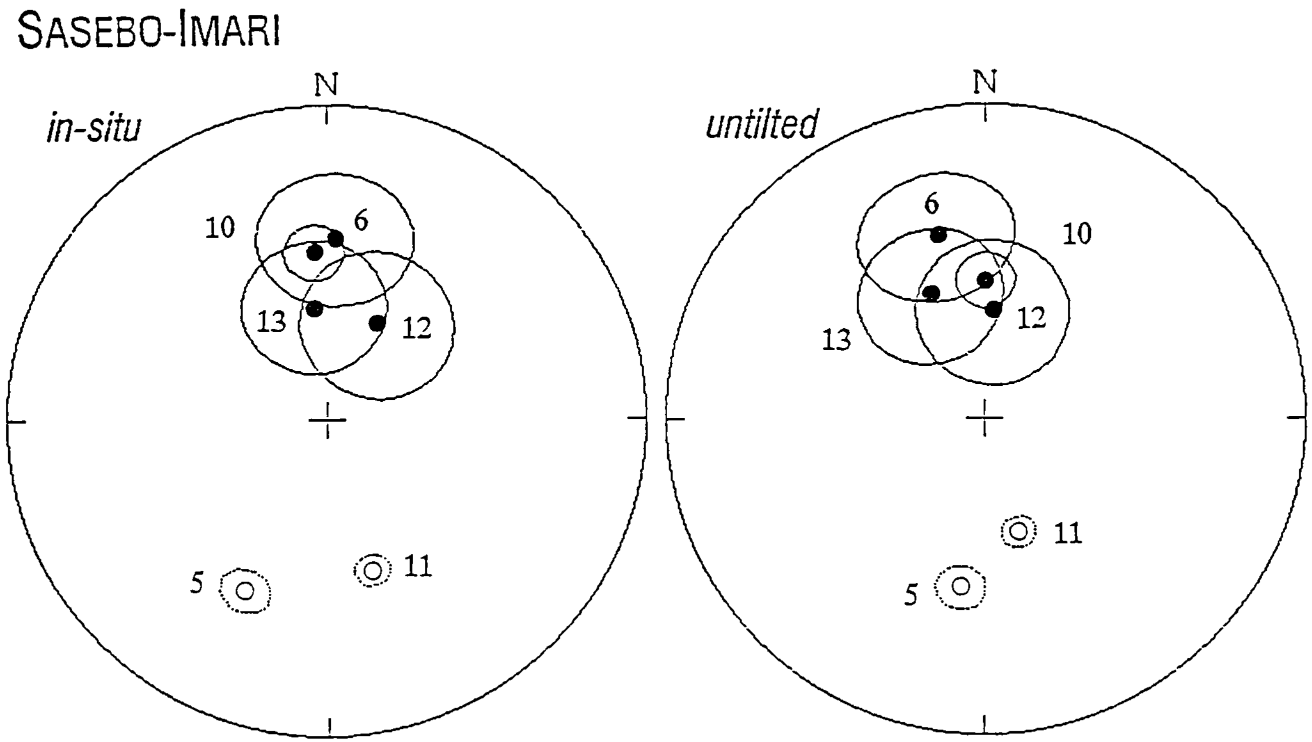

Fig. 9. Equal-area projections of in-situ and untilted site-mean directions from the Sasebo-Imari area. Solid and open symbols are on the lower and upper hemispheres, respectively. Ovals around the directions indicate 95% confidence limit. Numerals denote site numbers.

intensity and direction at the demagnetization levels approximately above 400°C or 25 mT. Below about 400°C or 25 mT, demagnetization results of eight sites among the 18 sites provided curved lines of the vector-end points decaying toward the origin of the diagrams, which were recognized as remagnetization circles on equal-area projection (Fig. 10). Those results indicated overlap of two magnetic components; one (the unstable component) was mainly isolated below about 240°C or 10 mT, and the other (the stable component) above about 240°C or 10 mT (Fig. 10). The site-mean direction of the stable components was calculated from the remagnetization circles for each site based on the method of McFadden and McElhinny (1988) as shown in Fig. 10.

The characteristic directions of the eight sites were shown and listed in Fig. 11 and Table 2, respectively. All characteristic directions except that of Site 3 showed a better antipodal relationship with the NE-SW trend after tilt correction. Although the fold test of McElhinny (1964) did not pass at the 95% confidence limit (k2/k1=2.14), the antipodal relationship suggested that the untilted directions of the seven sites represented the directions of the primary magnetic components acquired at the formation of the Ashiya Group. An anomalous direction of Site 3 may be attributed to a record of the transitional field during a geomagnetic reversal or a local tectonic disturbance around Site 3. The latter was probably less possible because the bedding of strata at site 3 shows approximately same trend to the general trend of the Ashiya Group. A mean direction was calculated from the untilted direction of the seven sites: D=35.9°, I=45.7°, α_{95}=11.5°. and k=28.7. This direction was regarded as a paleomagnetic direction of the Oligocene Ashiya Group.

The characteristic directions obtained from the Norimatsu shale member of the Yamaga Formation showed a change of the polarity (Fig. 12). The Norimatsu member was correlated to CP 18 of the calcareous nannoplankton biostratigraphy (Saito and Okada, 1984) and to the basal part of Zone P.21 (P.21a) of the planktonic foraminifera one (Tsuchi et al., 1987). This polarity change is correlated to that between Chron 10 and Chron 11 of the magnetostratigraphy (Fig. 12) after Berggren et al. (1985). The age of the Norimatsu member is assigned to about 31.2 Ma. The paleomagnetic direction of the Ashiya Group obtained in this study is thus regarded as the paleomagnetic direction of around 30 Ma for the Kita-Kyushu area.

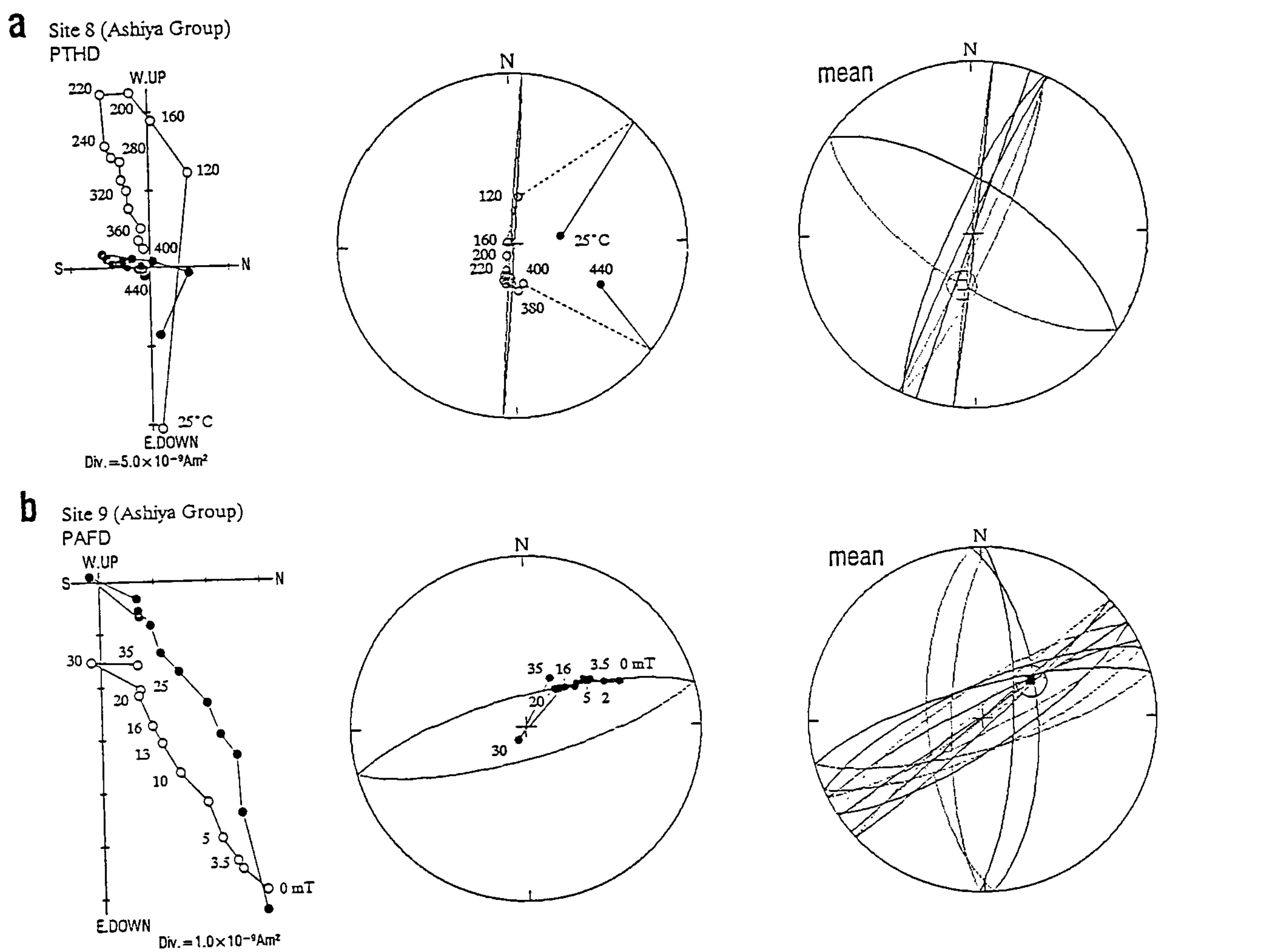

Fig. 10. Progressive demagnetization results from samples of the Ashiya Group in the Kita-Kyushu area shown on the vector-demagnetization diagrams (left) and equal-area projections (center). Each site-mean direction (square) was obtained from remagnetization circles based on the method of McFadden and McElhinny (1988; right).

Table 2. Paleomagnetic data from the Kita-Kyushu area.

Site (Lat, Lon)	N	levels	D	I	D*	I*	α_{95}	k	PLAT*	PLON*
Ashiya Group										
2 (33°55.5', 130°44.1')	7	GC 0-20mT	-126.9°	-18.1°	-114.5°	-49.8°	13.7°	29.5	35.5°	-155.2°
3 (33°56.1', 130°42.8')	7	GC 120-320°C	-132.4°	-1.9°	-133.6°	11.1°	6.8°	116.8	31.0°	-106.5°
5 (33°56.1', 130°42.3')	8	GC 120-280°C	-156.7°	-68.6°	-139.0°	-57.6°	6.1°	112.7	35.5°	-155.2°
8 (33°54.7', 130°40.2')	6	GC 120-360°C	-173.6°	-64.6°	-148.8°	-47.8°	7.0°	255.0	56.9°	-158.8°
9 (33°54.7' 130°40.2')	9	GC 0-20mT	46.7°	61.1°	51.2°	39.4°	7.5°	62.5	63.0°	-137.2°
16 (33°53.5', 130°42.3')	5	GC 2-20mT	-0.8°	47.3°	28.5°	37.9°	10.3°	118.8	43.9°	-138.7°
17 (33°52.9', 130°42.3')	4	GC 0-20mT	25.3°	56.5°	33.2°	43.0°	19.7°	81.5	61.9°	-120.0°
18 (33°53.1', 130°41.2')	6	GC 120-320°C	174.5°	-48.8°	-171.8°	-35.3°	1.6°	4618.4	59.9°	-78.3°
mean	7		22.8°	54.6°			17.1°	13.4		
mean*	7				35.9°	45.7°	11.5°	28.7	58.9°	-137.9°
									(α_{95}=13.3°, k=21.7)	

See Table 1 for explanation of symbols.

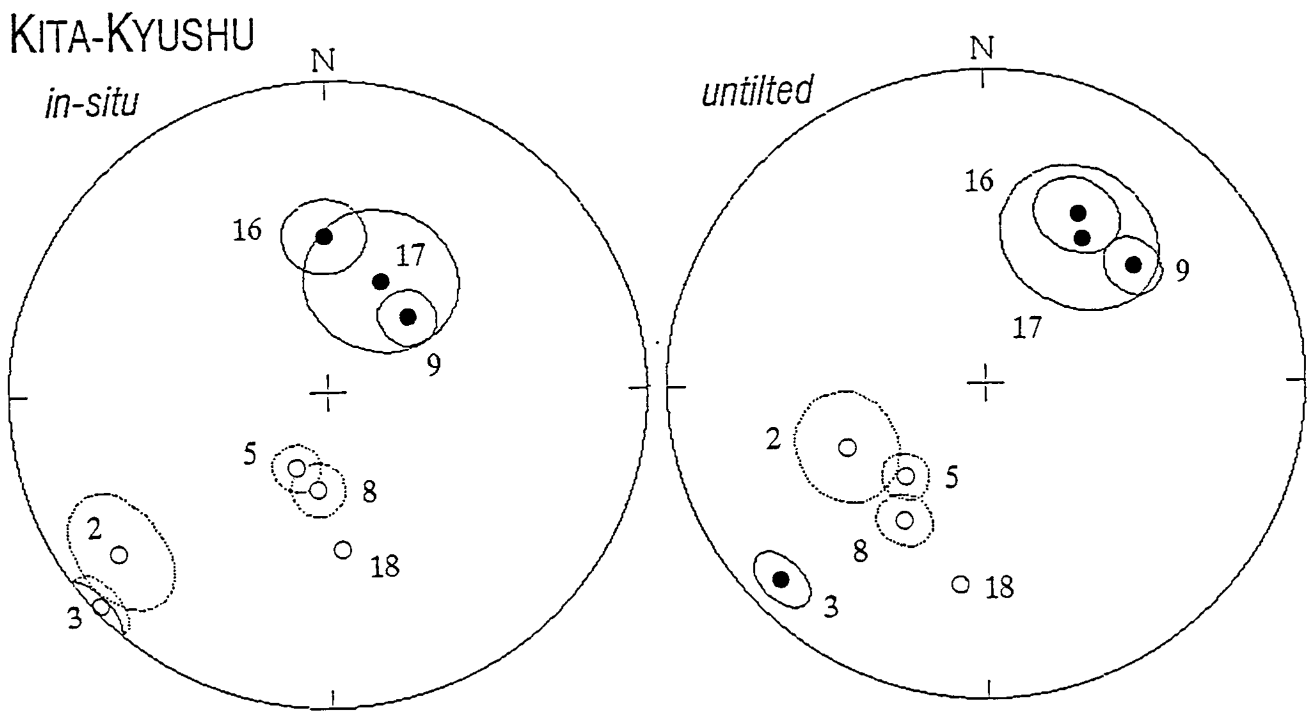

Fig. 11. Equal-area projections of in-situ and untilted site-mean directions from the Ashiya Group in the Kita-Kyushu area. Symbols are the same as in Fig. 9.

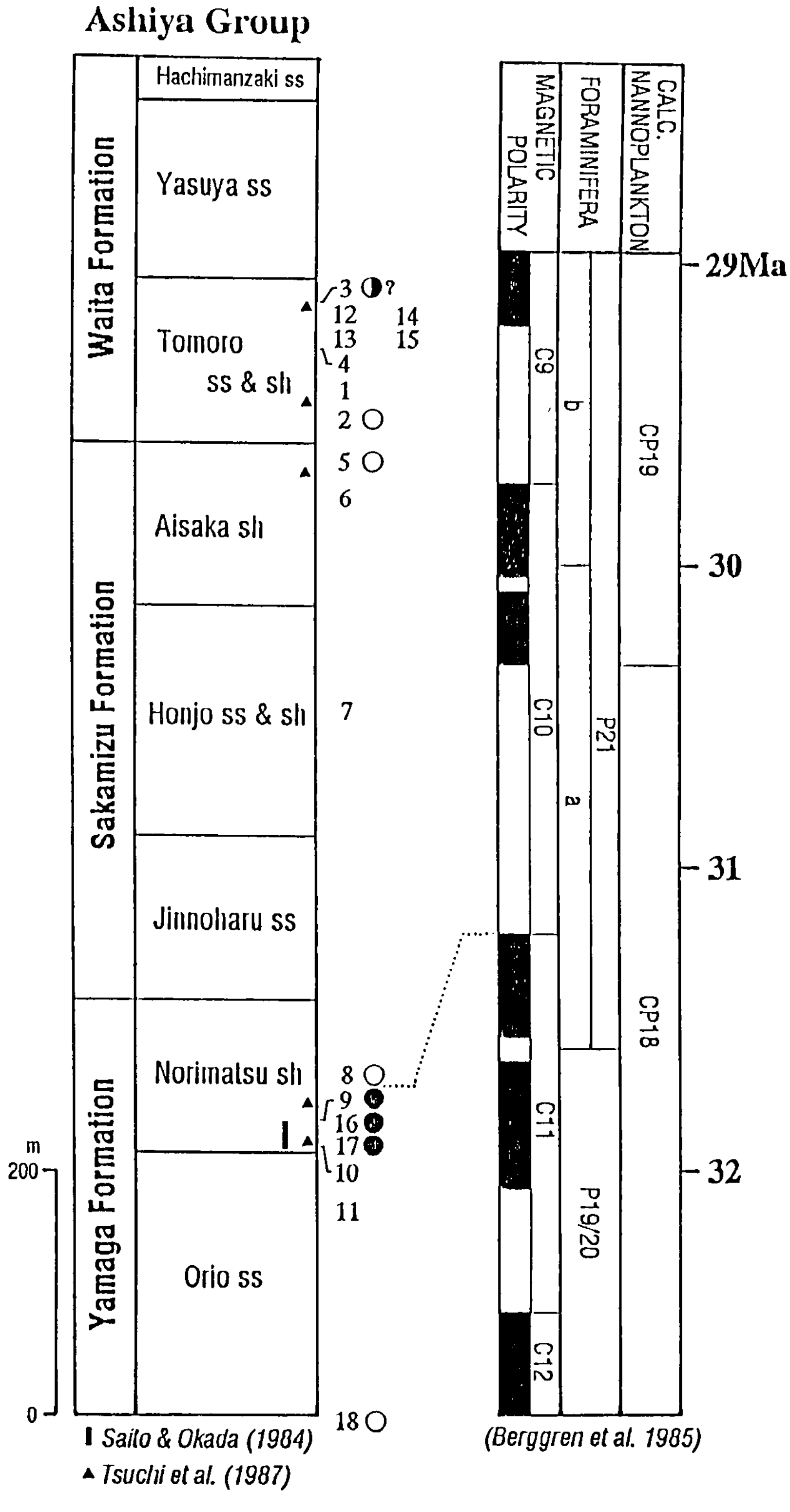

Fig. 12. Stratigraphical positions of paleomagnetic samples from the Ashiya Group. Numerals denote paleomagnetic sampling site numbers. Solid and open circles indicate normal and reverse polarity, respectively. Site 3 provided anomalous remanent direction as described in the text. Micropaleontological sites are indicated by solid triangles (Tsuchi et al., 1987) and bars (Saito and Okada, 1984). Cenozoic time scale of Berggren et al. (1985) is adopted.

Amakusa area

The specimens of all sites but Site 8 from the Akasaki Group had intensity of initial NRM of the order of 10^{-8} to 10^{-7} Am^2. The intensities of the specimens of Site 8 were the order of 10^{-9} Am^2. Five sites among the eight sites yielded the stable components with higher unblocking temperature above 600°C during progressive thermal demagnetization (Fig. 13). The maximum AF demagnetization (100 mT) could not isolate the components similar to the higher temperature components (Fig. 13).

The specimens of Sites 1 and 6 yielded essentially single stable components. The linear decay of the magnetic vector was clearly recognized in the temperature range approximately between 590°C and 650°C (Fig. 13a). The specimens of Sites 4, 5 and 14 provided two components (Figs. 13b and c). One was isolated in the lower temperature range between 120°C and 280°C for the specimens of Sites 4 and 5 (Fig. 13b) and in the range from 120°C to 440°C or 500° for those of Site 14 (Fig. 13c). The other components were isolated in the higher temperature range above 280°C for Sites 4 and 5, especially between 590° and 650°, and in the range between 590°C and 680°C for Site 14. The magnetic vector of the higher-temperature component decayed uniformly toward the origin on the diagram.

The site-mean directions of the components with high unblocking temperature from Sites 1, 4, 5, 6 and 14 showed a tight cluster with southwest declination and negative inclination in in-situ coordinates, while the untilted directions were fairly scattered (Fig. 14). The common magnetic component was regarded as a secondary component acquired after the formation of the fold system on the Kamishima Island and the Uto Peninsula. The reverse polarity of the component indicated that the component had been acquired before Brunhes Chron. Demagnetization results implied hematite to be the remanence carrier of the component. Judging from secondary origin of hematite in the Akasaki Group (Miki and Matsueda, 1985), the components carried by hematite was chemically acquired.

A mean direction calculated from the in-situ directions of Sites 1, 4, 5, 6 and 14 was D=-148.3°, I=-50.4°, α_{95}=7.5°, and k=105.4 (Table 3). The mean direction was significantly different with the expected directions of the present geomagnetic field and the geocentric axial dipole field at this area.

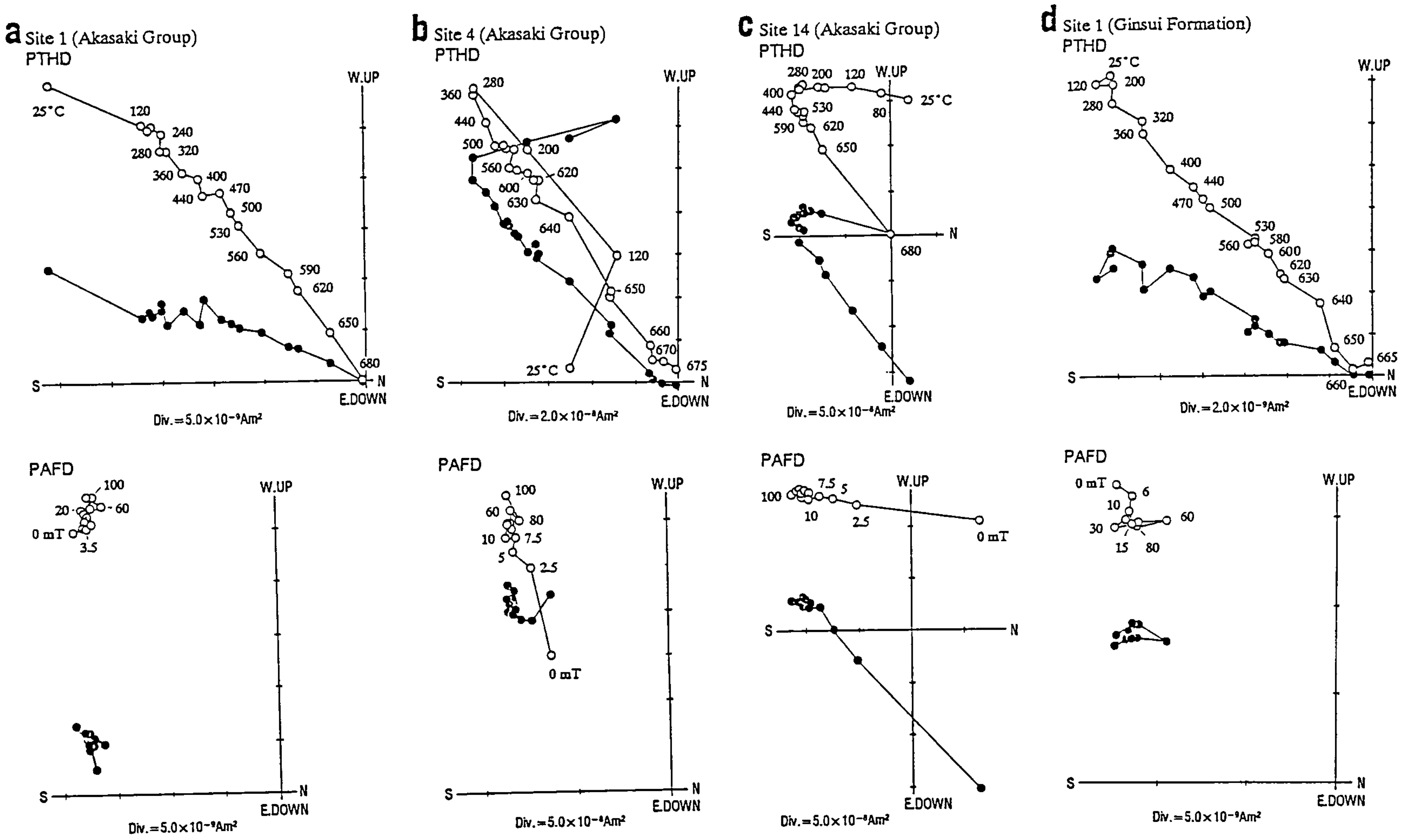

Fig. 13. Vector-demagnetization diagrams of progressive demagnetization for samples from the Akasaki Group in the Amakusa area (a, b and c) and the Ginsui Formation in the Omuta area (d). Symbols are the same as in Fig. 8-1.

Table 3. Paleomagnetic data from the Amakusa and Omuta areas.

Site (Lat,Lon)	N	levels	D	I	D*	I*	α_{95}	k	PLAT	PLON
Amakusa area (Akasaki Group)										
1 (32°39.3', 130°31.2')	4	LA 590-680°C	-156.3°	-51.8°	-165.8°	-59.4°	6.1°	226.1	70.1°	-145.3°
4 (32°30.2', 130°25.4')	7	LA 360-650°C	-139.1°	-47.8°	-149.1°	-46.6°	3.2°	357.7	54.9°	-144.7°
5 (32°23.3', 130°21.3')	6	LA 360-650°C	-149.5°	-52.2°	-168.5°	-26.0°	3.4°	387.0	64.4°	-148.9°
6 (32°23.3', 130°21.2')	5	LA 560-650°C	-142.2°	-49.9°	-170.5°	-29.2°	9.0°	73.7	57.9°	-146.9°
14 (32°33.9', 130°28.6')	6	LA 590-680°C	-163.7°	-49.8°	-134.9°	-57.1°	2.3°	886.4	76.0°	-135.9°
mean	5		-150.0°	-50.7			6.4°	145.6	64.7°	-145.2°
									(α_{95}=8.4°, k=84.5)	
mean*	5				-159.1°	-44.4°	17.9°	19.1		
Omuta area (Ginsui Formation)										
1 (33°05.1', 130°40.0')	6	LA 580-660°C	-150.0°	-44.2°	-144.7°	-68.0°	6.0°	127.2	63.0°	-132.0°

See Table 1 for explanation of symbols.

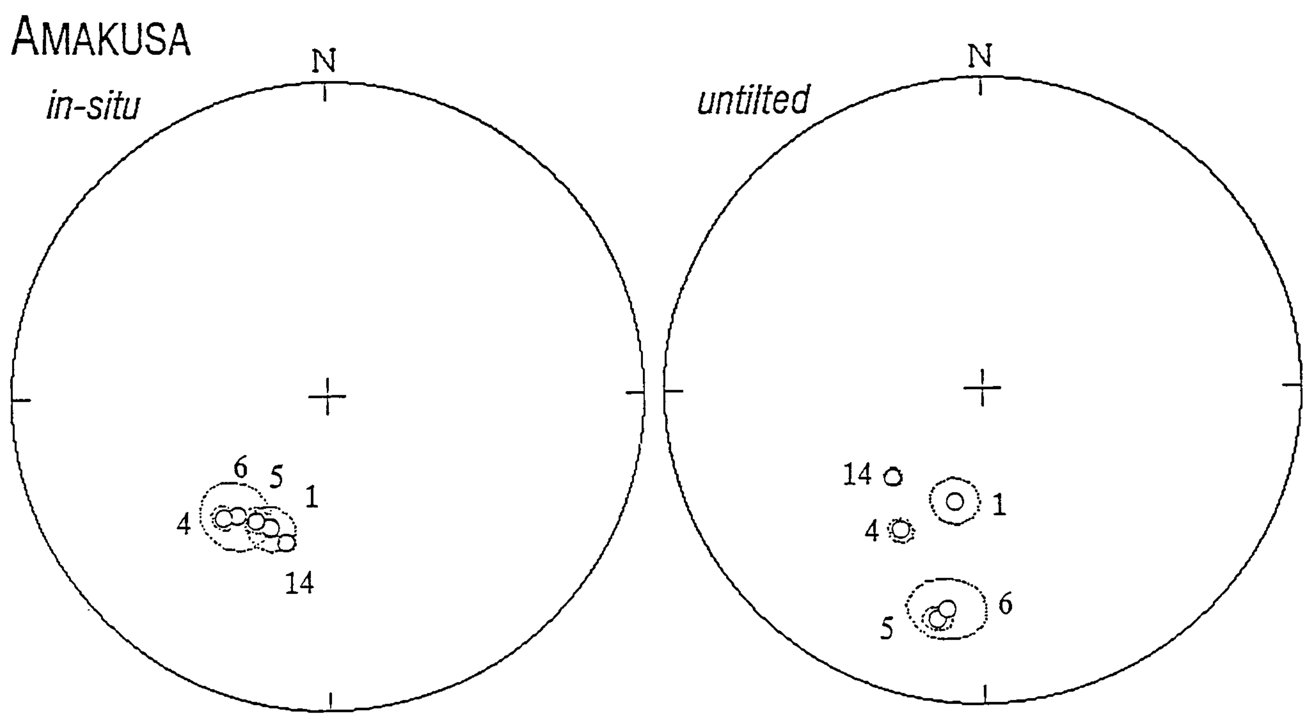

Fig. 14. Equal-area projections of in-situ and untilted site-mean directions from the Akasaki Group in the Amakusa area. Symbols are the same as in Fig. 9.

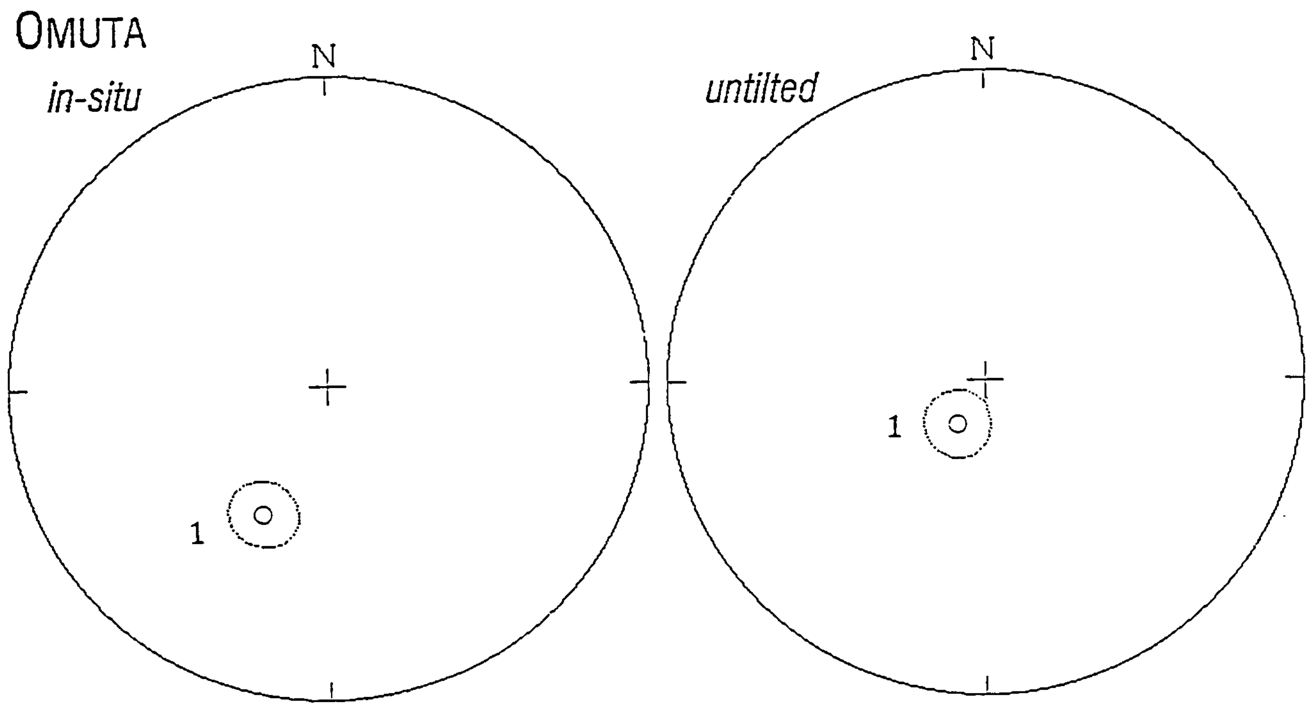

Fig. 15. Equal-area projections of in-situ and untilted site-mean direction from the Ginsui Formation in the Omuta area. Symbols are the same as in Fig. 9.

Omuta area

The specimens from the Ginsui Formation showed variable intensity of initial NRMs ranging between the order of 10^{-10} to 10^{-8} Am^2 in each site except Site 1. The intensities of the specimens of Site 1 was about 2×10^{-8} Am^2.

The specimens of Site 1 provided the stable components by the thermal demagnetization. The components showed approximate linear decay toward the origin on the diagram in the temperature range from 500° to 640° (Fig. 13d). Their NRM directions and intensities did not change during progressive AF demagnetization (Fig. 13d). These demagnetization results indicated that hematite was the carrier of the stable component from Site 1. The site-mean direction of the stable components from Site 1 had southwest declination with negative polarity in in-situ coordinates (Fig. 15 and Table 3). It was close to the characteristic remanent directions from the Akasaki Group in the Amakusa area in in-situ coordinates.

Unfortunately, no directional data but Site 1 of the Ginsui Formation have been reported from the sediments in the Omuta area. It was impossible to judge whether or not the stable component of Site 1 was primary. The remanent direction of Site 1 was discarded from the further consideration.

3-3. The estimation of tectonic displacements

Virtual geomagnetic pole (VGP) positions for the Sasebo- Imari and Kita-Kyushu areas are shown in Fig. 16, together with the paleomagnetic poles of 20 and 30 Ma for northern Eurasia (Irving and Irving, 1982) and the main part of Southwest Japan (Otofuji and Matsuda, 1987). The discrepancies among these poles represent relative tectonic displacements among these areas. Taking the paleomagnetic poles as references, the amount of tectonic displacement for the Sasebo-Imari and Kita-Kyushu areas are calculated from the obtained paleomagnetic directions (Table 4) based on the definitions of Beck (1980) and Demarest (1983).

The VGP for the Sasebo-Imari area is close to the paleomagnetic poles for northern Eurasia, pointing the geographic north. Taking the 20 Ma paleomagnetic pole of northern Eurasia (Irving and Irving, 1982) as a reference, the paleomagnetic direction for the Sasebo-Imari area shows no significant discrepancies in both declination and inclination. It

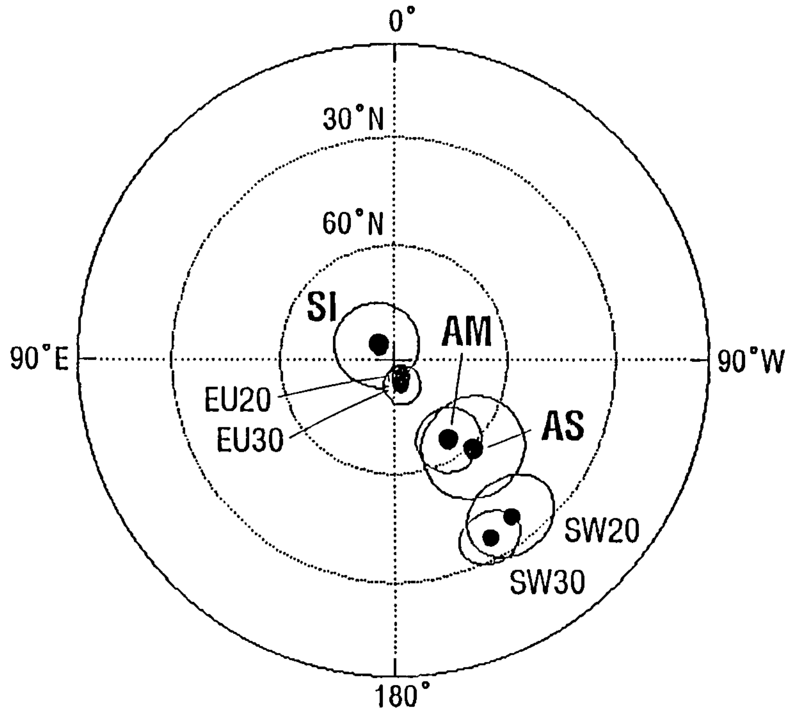

Fig. 16. Equal-area projections of virtual geomagnetic poles for the Sasebo-Imari (SI), Kita-Kyushu (AS), and Amakusa (AM) areas. EU20 and EU30 are northern Eurasia paleomagnetic poles for 20 and 30 Ma (Irving and Irving, 1982). SW20 and SW30 are the paleomagnetic poles for 20 and 30 Ma from the main part of Southwest Japan (Otofuji and Matsuda, 1987).

Table 4. Tectonic parameters (R, F) and their 95% uncertainties of (ΔR. ΔF) for the Sasebo-Imari and Kita-Kyushu areas based on the definitions of Beck (1980) and Demarest (1983).

Area (Lat, Lon)	Reference	R	ΔR	F	ΔF
Sasebo-Imari	EU20	-12.6°	12.9°	1.7°	8.0°
(33.3°N, 129.8°E)	SW20	-65.6°	15.6°	-14.3°	14.2°
Kita-Kyushu	EU30	27.8°	13.8°	11.1°	9.7°
(34.9°N, 130.7°E)	SW30	-28.2°	14.5°	1.6°	11.3°

R and F are the discrepancies in declination and inclination. respectively. between the observed and expected directions. The expected directions are calculated from reference paleomagnetic poles (Reference; See Fig. 16 footnotes). R and F represent relative rotation and north-to-south translation. respectively. Positive values of R and F indicate clockwise rotation and northward translation. respectively.

is indicated that the Sasebo-Imari area has been subjected to little significant tectonic displacement relative to northern Eurasia since about 30 Ma.

The VGP for the Kita-Kyushu area is different from the paleomagnetic poles for northern Eurasia and the main part of Southwest Japan. The paleomagnetic direction for the Kita-Kyushu area yields a significant discrepancy of 27.8° ± 13.8° in declination when the 30 Ma paleomagnetic pole of northern Eurasia (Irving and Irving, 1982) is taken as a reference. It is suggested that the Kita-Kyushu area had been subjected to a CW rotation of 28° relative to northern Eurasia since about 30 Ma. The discrepancy in inclination (11.1° ± 9.7°) is also significant, which may imply northward translation relative to northern Eurasia. This discrepancy is however compatible with uncertainty at 95% confidence limit. The northward translation is not very convincing. Further work is needed to establish its significance. On the other hand, taking the 30 Ma paleomagnetic pole of the main part of Southwest Japan (Otofuji and Matsuda, 1987) as a reference, the discrepancy in declination is significant (-28.2° ± 14.5°). It is indicated that the Kita-Kyushu area have been subjected to a counter-clockwise (CCW) rotation relative to the main part of Southwest Japan since about 30 Ma.

The VGP for the secondary component directions from the Akasaki Group in the Uto Peninsula and the Kamishima Island is different from the geographic north, and it is close to the VGP for the Kita-Kyushu area (Fig. 16). The Uto Peninsula and the Kamishima Island might have shared a rotational motion to which the Kita-Kyushu area was subjected. A tilting about a horizontal axis is also possible to explain the discrepancy between the VGP of the Akasaki Group and the geographic north. The discrepancy implies a tilting of about 25° toward the WNW direction around a horizontal axis with the strike of about N13°E. However, the geologic structures of the Paleogene sequences on the Uto Peninsula and the Kamishima Island do not appear to support the implied tilting of the whole area.

4. Discussion

4-1. Rotational motions in the northern Kyushu Island

Declinations of paleomagnetic data from the northern Kyushu Island and the neighboring regions are shown in Fig. 17. The deflection from the north in declination represents the sense of rotational motion. From the view point of the deflection, two different tectonic blocks are inferred in the northern Kyushu Island, namely the main part of the northern Kyushu Island (Northern Kyushu) and the western part (Western Kyushu). The CCW deflections from the Tsushima and Goto Islands indicate that the Tsushima Strait area belongs to another tectonic block. The CCW deflections was interpreted as the CCW block rotations in the Tsushima Strait area at around 15 Ma (Ishikawa et al., 1989; Ishikawa and Tagami, 1991).

The CW deflected directions characterize Northern Kyushu. The CW deflections can be explained by the CW rotation indicated by the paleomagnetic direction for the Kita-Kyushu area, although the remanent directions of the Cretaceous granites and the Akasaki Group in the Amakusa area are not corrected for tilting. Torii and Ishikawa (1986) found non-deflected paleomagnetic directions from the Middle Miocene Ono volcanic rocks and Sobosan-Okueyama volcano-plutonic complex (Fig. 17). The K-Ar ages of 13-14 Ma have been reported from these igneous rocks (Shibata and Ono, 1974; Shibata, 1978; Tatsumi et al., 1980). It is suggested that the CW rotation of Northern Kyushu occurred sometime between 30 Ma and 14 Ma.

Western Kyushu yields non-deflected directions. The paleomagnetic direction for the Sasebo-Imari area shows no significant rotation of Western Kyushu relative to northern Eurasia since about 30 Ma. It is supported by non-deflected remanent direction of the Late Miocene Kita-Matsuura basalts (Creer and Ispir, 1970; Nomura, 1967; Ozima et al, 1968).

4-2. The CW rotation of Southwest Japan and associated tectonics

Southwest Japan has been regarded as a coherent rigid block which was subjected to the CW rotation of about 50° at about 15 Ma (e.g., Otofuji and Matsuda, 1987). In terms of the CW rotation of 50° at 15 Ma, both Northern Kyushu and Western Kyushu, as well as the Tsushima Strait area (Ishikawa and Tagami, 1991), are excluded from the Southwest

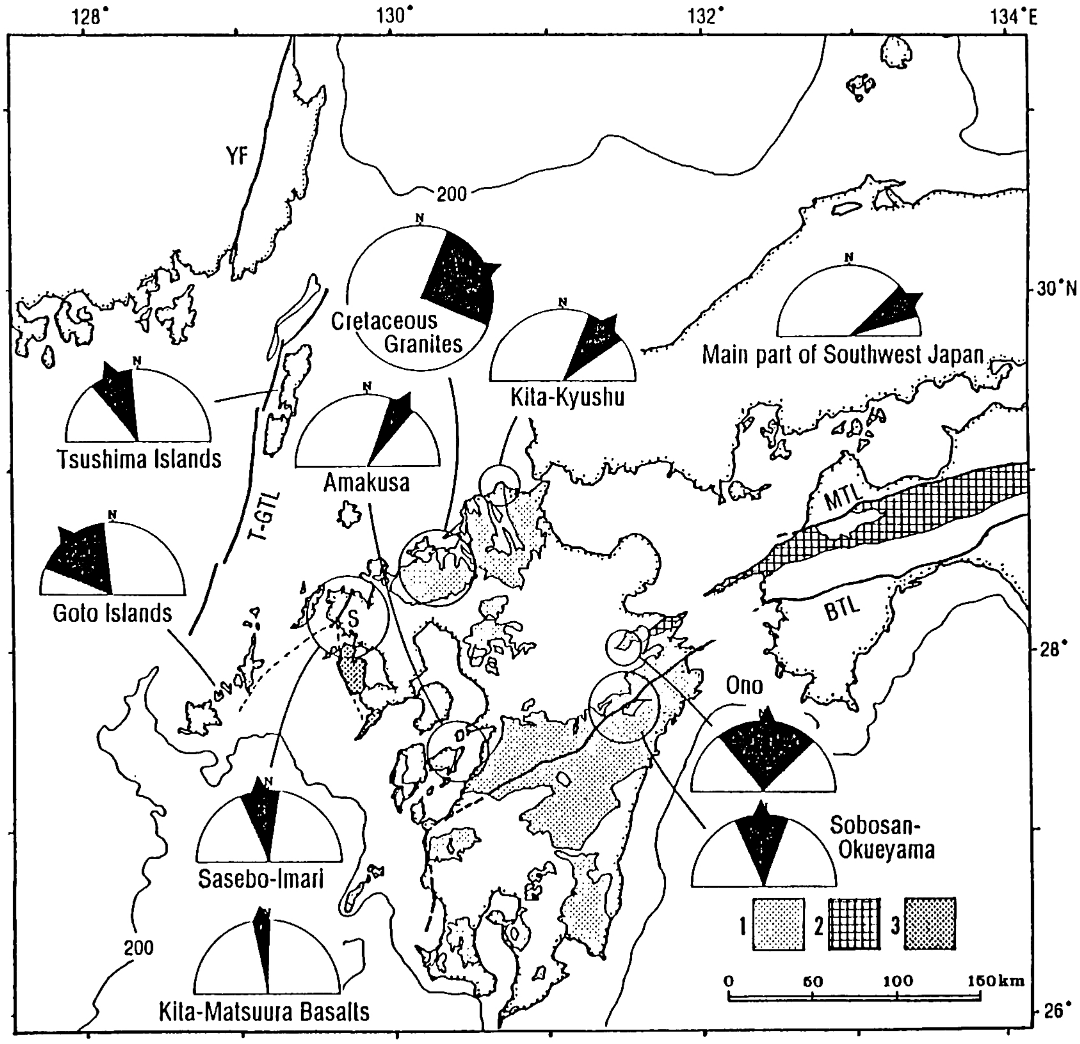

Fig. 17. Paleomagnetic declinations from the northern Kyushu Island with 95% confidence limit (Ozima, et al., 1968; Torii and Ishikawa, 1986; Otofuji and Matsuda, 1987; Ishikawa et al., 1989; Ishikawa, 1990; Ishikawa and Tagami, 1991). Goto Islands represents a mean declination of the Goto Group recalculated from Ishikawa and Tagami (1991). Kita-Matsuura Basalts represents a mean declination recalculated from remanent directions of Ozima et al. (1968) with smaller α_{95} than 20°. Main part of Southwest Japan is the 20 Ma paleomagnetic direction of Otofuji and Matsuda (1987). 1:pre-Neogene geologic units in the Kyushu Island. 2:Sanbagawa metamorphic rocks. 3:Nagasaki metamorphic rocks. YF:Yangsan Fault. T-GTL:Tsushima-Goto tectonic line. S:Sasagawa thrust.

Japan block.

The extent of the Southwest Japan block has been assumed based on the ENE-WSW trending zonal structure of the pre-Neogene geologic units in Southwest Japan (e.g., Otofuji and Matsuda, 1987). The high-P/T metamorphic belt in Southwest Japan, the Sanbagawa metamorphic rocks, forms one part of the zonal structure of Southwest Japan, and its western extent is somewhat obscured (Fig. 17). In Western Kyushu, the high-P/T Nagasaki metamorphic rocks with N-S trending structure is distributed (Fig. 17). Faure at al. (1988) correlated the Nagasaki metamorphic rocks to the Sanbagawa metamorphic rocks based on the similarities of lithology, metamorphism, stratigraphic and radiometric ages, and deformation style. The similarities was interpreted to show that the two metamorphic rocks had been formed by the same geodynamic processes in a tectonic belt (Faure et al., 1988). However, the two metamorphic rocks show different structural trend, implying Western Kyushu to be a different tectonic block from Southwest Japan (Kizaki, 1979, 1986; Faure at al., 1988). The difference between Western Kyushu and Southwest Japan is also indicated paleomagnetically by this study. The inconsistency in structural trend strongly suggests the differential rotation between Western Kyushu and Southwest Japan.

The CW rotation of Northern Kyushu can be attributed to the CW rotation of Southwest Japan at about 15 Ma because the zonal structure in the main part of Southwest Japan is continuously traced to Northern Kyushu (Ozawa, et al., 1984). The significant differential rotation between Northern Kyushu and the main part of Southwest Japan suggests smaller amount of CW rotation for the western part of Southwest Japan during the CW rotation of the whole Southwest Japan. Murata (1987a,b) and Kano et al. (1990) pointed out that the structural trend of the pre-Neogene geologic units is different between the Kyushu Island and the main part of Southwest Japan; the trend is N55°±5°E in the Kyushu Island and N75°±5°E in the main part of Southwest Japan (Kano et al. 1990). The discrepancy in the structural trend was probably caused by the differential rotation between the western and the main part of Southwest Japan during the CW rotation. The rigid block rotation model for the CW rotation of Southwest Japan (e.g., Otofuji and Matsuda, 1987) should be modified so as to accept small deformation on the western end.

At the time of the CW rotation of Southwest Japan, the Tsushima and Goto Island in the Tsushima Strait area were rotated CCW (Ishikawa and Tagami, 1991), and Western Kyushu was not subjected to significant rotation. In the Tsushima Strait area, several large scale faults are found by seismic investigations (e.g., Tomita et al., 1975; Katsura and Nagano, 1976). The Tsushima and Goto Islands are regarded as fault-bounded blocks (Katsura and Nagano, 1976). The CCW rotations of the two archipelagoes were interpreted as block rotations in response to the fault movements in the Tsushima Strait area, especially the sinistral motion of the Tsushima-Goto tectonic line (Ishikawa and Tagami, 1991; Fig. 17). On the other hand, any large scale faults bounding the blocks are not observed in geological features between Western Kyushu and Northern Kyushu, as well as in Southwest Japan. The plastic deformation might have been caused by the CW rotation of Southwest Japan around the boundary regions.

The Tsushima Strait area was subjected to compressive deformation due to NW-SE compressive force after the deposition of pre-middle Miocene sediments (Shimada, 1977; Hoshino, 1985). The sinistral motion of the NNE-SSW trending Tsushima-Goto tectonic line and other fault movements in the area occurred during the compressive deformation event (Katsura and Nagano, 1976; Shimada, 1977; Hoshino, 1985), which caused the CCW block rotations in the Tsushima Strait area (Ishikawa and Tagami, 1991). These tectonic features probably suggest the transpressional tectonic regime in the Tsushima Strait area (Koga, 1982). Ishikawa and Tagami (1991) estimated the age of the compressive deformation event. They suggested that the compressive deformation event was coeval with the CW rotation of Southwest Japan.

The transpressional tectonic regime in the Tsushima Strait area indicates the convergence of the western margin of Southwest Japan toward the Korean Peninsula during the CW rotation. This can be attributed to the CW rotation of Southwest Japan about a pivot placed on the western part (Fig. 18). The rotation pivot has been located at 34°N and 129°E in the Tsushima Strait area (Otofuji and Matsuda, 1983). However, the CW rotation of Southwest Japan about the pivot of Otofuji and Matsuda (1983) seems to bring divergent motion of the western margin away from the Korean Peninsula.

Associated with the convergence of the western margin of Southwest Japan, Western Kyushu was probably translated northwestward (Fig. 18). The paleomagnetic direction for the Sasebo-Imari area shows no significant tectonic displacement since about 30 Ma (Table

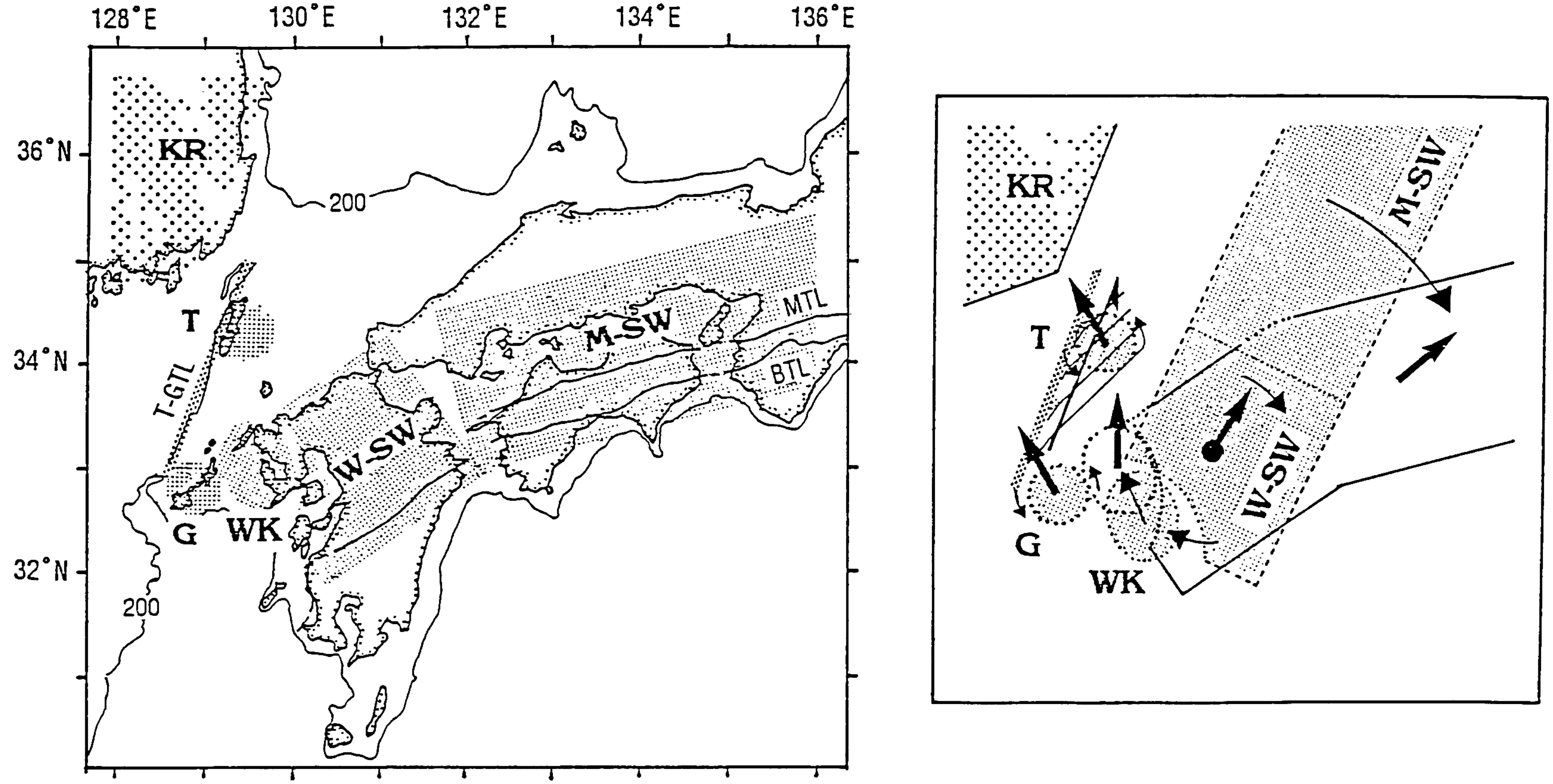

Fig. 18. Schematic diagram illustrating the clockwise (CW) rotation of Southwest Japan and associated movements around the western margin. Southwest Japan is rotated about a pivot on its western part, resulting in convergence of the western margin toward the Korean Peninsula (KR) and associated northward translation of Western Kyushu (WK). Due to the convergent motions, the Tsushima Strait area is subjected to transpressional deformation. The Tsushima-Goto tectonic line (T-GTL) is moved sinistrally. Associated with the convergent tectonics, the Tsushima (T) and Goto (G) Islands are rotated counter-clockwise. The western part of Southwest Japan (W-SW) is rotated smaller than the main part (M-SW). Each thick arrow represents paleomagnetic declination for each tectonic block. MTL: Median Tectonic Line. BTL: Butsuzo Tectonic Line.

4). However, the amount of the northwestward translation appears to be smaller than which can be detected significantly by means of paleomagnetism. The possibility of the northwestward translation can not be rejected paleomagnetically. The NE-SW trending Sasagawa thrust in the Sasebo-Imari area (Fig. 17) activated in early to middle Miocene time (Nagahama, 1965). The time and sense of the thrust movement possibly imply the northwestward translation of the NW Kyushu during the transpressional event in the Tsushima Strait area.

4-3. The mode of drifting of Southwest Japan during the Japan Sea opening

The convergent tectonics around the western part of Southwest Japan during its CW rotation suggest that the western part had been located southward to the present position before its CW rotation (Fig. 18). The correlation of on-land geology between the Korean Peninsula and Southwest Japan has indicated that the western part of Southwest Japan had been situated near the Korean Peninsula more closely than the present position in Cretaceous time (Ichikawa, 1972; Kimura, 1974; Shimazaki et al., 1981; Hoshino, 1985). It is inferred that the southward drift of Southwest Japan relative to the Asian continent occurred prior to the CW rotation. Any significant rotational motion prior to the CW rotation has not been detected paleomagnetically (Hayashida et al., 1991; Otofuji et al., 1985c, 1991). The mode of the southward drift of Southwest Japan prior to its CW rotation is considered to be translation (Hayashida et al., 1991; Ishikawa and Tagami, 1991).

The Oligocene to early Miocene sediments on the Tsushima Islands, the Taishu Group, is composed of shallow marine sediments. The direction of paleocurrent in the group was estimated to trend northwestward (Nagahama et al., 1966). The strata correlated to the Taishu Group has been recognized on seismic profiles in the southern margin of the Tsushima basin (Minami, 1979). The deposition of the Taishu Group possibly suggests the formation of a sedimentary basin with marine environment behind the western part of Southwest Japan prior to the CW rotation of Southwest Japan (Kimura, 1974). The sedimentary basin of the Oligocene to early Miocene marine sediments may have been caused by the southward translation of Southwest Japan.

The southward translation of Southwest Japan prior to the CW rotation may have been related to the formation of the Japan Sea before 15 Ma. Geological and geophysical data from on-land and the Japan Sea have documented the older initiation of the Japan Sea before about 15 Ma. Early Miocene lake and marine sediments, deposited during the initial stage of the formation of the Japan Sea, are distributed along the Japan Sea coast of Southwest Japan (Huzioka, 1972; Kano and Yanagisawa, 1989; Koizumi, 1988). Seismic reflection profiles and geologic data from exploratory wells in the southwestern margin of the Tsushima basin indicated the existence of Early Miocene or older marine sediments in the region (Minami, 1979; Chough and Barg, 1987). Tamaki (1986) estimated 30 to 15 Ma for the Japan and Yamato basin formations based on sediment stratigraphy, basement depth and heat flow data. Isezaki (1986) examined the magnetic anomalies in the Japan basin and suggested 19-15 Ma for the formation age of the Japan basin. Geologic data from the Legs 127 and 128 of Ocean Drilling Program indicated that the Yamato Basin was formed in the early Miocene before 19 Ma (Ingle et al., 1990; Leg 127 and Leg 128 Shipboard Scientific Parties, 1990; Tamaki et al., 1990). Based on K-Ar and Ar-Ar ages for volcanic rocks obtained by Legs 127 and 128 and dredged samples from the Japan Sea floor, Kaneoka (1990 and 1991) suggested that the Japan and Yamato basins were formed between 25 Ma to 17 Ma. The mode of the drifting of Southwest Japan during the formation of the Japan Sea may be summarized as follows: southward translation in Early Miocene or older and subsequent CW rotation at 15 Ma about a pivot on the western part of Southwest Japan. The mode of the drifting is likely linked to the parallel opening and subsequent fan-shape opening of the southwestern part of the Japan Sea.

The opening mode of the Japan Sea suggests that larger extension occurred behind the eastern part of Southwest Japan at about 15 Ma, superimposed on the extension of the whole area behind Southwest Japan. The Japan, Yamato, and Tsushima basins are situated behind Southwest Japan (Fig. 1). The Japan basin is the largest basin in the Japan Sea, situating in the northern half of the Japan Sea. The Yamato and Tsushima basins are located at the south of the Japan basin. The Yamato basin behind the eastern part of Southwest Japan is larger than the Tsushima basin. The superimposed extension may have been related to the formation process of the Yamato basin. The formation of the Yamato Basin started at about 19 Ma (e.g., Legs 127 and 128 of Ocean Drilling Program, 1990), while the fan-shape opening accompanied with the CW rotation of Southwest Japan occurred at about 15 Ma. A mechanism resulting in an abrupt large extension may have been required for the formation process of the Yamato basin.

5. Conclusions

On the basis of the paleomagnetic data from Eocene to Miocene sediments on the northern Kyushu Island, the landmass is divided into two different tectonic blocks. Northern Kyushu was subjected to the CW rotation of 27.8° ± 13.8° relative to northern Eurasia between 30 Ma and 14 Ma, while no significant rotation has taken place in Western Kyushu since 30 Ma.

Considering regional geological structures, the paleomagnetic results indicate that the extent of Southwest Japan which experienced the CW rotation at about 15 Ma is truncated at the west of Northern Kyushu. The smaller amount of CW rotation (~28°) is suggested for the western part of Southwest Japan (Northern Kyushu) when the main part of Southwest Japan was rotated ~50° The differential rotation suggests deformation on the western part of the rotated block during the CW rotation. The coherent rigid block model for the whole Southwest Japan during the CW rotation (e.g., Otofuji et al., 1991) should be modified so as to accept deformation on the edge of the block.

The transpressional deformation event in the Tsushima Strait area was coeval with the CW rotation of Southwest Japan (Ishikawa and Tagami, 1991). The deformation event was caused by the CW rotation of Southwest Japan about a pivot placed on the western part. The convergence of the western margin of Southwest Japan during the CW rotation resulted in the northwestward translation of Western Kyushu. Associated with the convergent tectonics, the CCW block rotations of the fault-bounded blocks occurred in the Tsushima Strait area along the NNE-SSW fault zone.

The convergent tectonics on the western margin of Southwest Japan suggest that the western part of Southwest Japan had been situated southward relative to the present position prior to the CW rotation. Such a paleoposition of the western part may indicate the southward translation of Southwest Japan from the Asian continent prior to the CW rotation. The southward translation may imply the parallel opening of the southwestern part of the Japan Sea before the fan-shape spreading at about 15 Ma.

Acknowledgements

I am indebted to Prof. S. Nishimura and Assoc. Prof. M. Torii of Dept. Geology and Mineralogy of Kyoto University for their continuing advice, encouragements, and discussions throughout this work, and for their critical reading of the manuscript.

I performed paleomagnetic measurements at the paleomagnetic laboratory of Dept. Geology and Mineralogy of Kyoto University, by courtesy of Assoc. Prof. M. Torii and other members of the laboratory. I am much grateful to them. The assistance of H. Oda and H. Momose in the field work is also appreciated.

I would like to express my thanks to Drs. S. Tomita and T. Miki of Kyushu University for their kindly advice and comments for this work. I would like to acknowledge the comments of Prof. R. Tsuchi of Shizuoka University.

My sincere thanks are due to Drs. Y. Tatsumi and T. Tagami of Kyoto University, Dr. A. Hayashida of Doshisha University, and Dr. H. Shibuya of the University of Osaka Prefecture for their helpful discussions and encouragements throughout this work.

I would like to thank Prof. K. Chinzei, Prof. S. Banno, and Assoc. Prof. K. Mori of Kyoto University for their critical reviewing of the manuscript.

I would like to appreciate the members of Division of Physical Geology, Dept. Geology and Mineralogy of Kyoto University, for their discussions during the reduction of the manuscript.

I also appreciate Prof. S. Matsushima, Prof. K. Ishizaka, Assoc. Prof. O. Tamada, Assoc. Prof. S. Sakai, T. Okura, S. Takagishi of College of Liberal Arts and Sciences, Kyoto University, for their encouragements and supports throughout this work.

Last of all, I thank Kumiko I.

This work was supported in part by a Grant-in-Aid (No. 01740453) from the Japanese Ministry of Education, Science and Culture.

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